NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

A DECISION SUPPORT SYSTEM FOR EVALUATING SYSTEMS OF UNDERSEA SENSORS AND WEAPONS

by

Team Mental Focus
Cohort 142O

December 2015

Project Advisors:	Bonnie Young
	Paul Shebalin
Second Reader:	Richard Williams

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704–0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** December 2015	**3. REPORT TYPE AND DATES COVERED** Capstone Project Report	
4. TITLE AND SUBTITLE A DECISION SUPPORT SYSTEM FOR EVALUATING SYSTEMS OF UNDERSEA SENSORS AND WEAPONS			**5. FUNDING NUMBERS**
6. AUTHOR(S) Systems Engineering Cohort 142O/Team Mental Focus			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

This project developed and analyzed the requirements for a decision support system capable of simulating future naval mine warfare scenarios. As the U.S. Navy explores replacing legacy naval mines with new systems of undersea weapons, it requires the supporting tools to evaluate and predict the effectiveness of these system concepts. While current naval minefield modeling and simulation capabilities provide planners with the capability to design and evaluate the effectiveness of minefields using legacy naval mine capabilities, they are not adequate for the planning and performance modeling of new concepts under consideration. The project addressed gaps in the Navy's capability to simulate mine warfare scenarios involving arrays of distributed sensors linked with autonomous mobile weapons by reviewing the current innovations in naval mine warfare development, verifying the gap in current modeling and simulation capabilities, and using systems engineering processes to derive solution requirements. Analysis conducted using prototype simulation capabilities, developed as part of this project, indicates that these future systems will likely outperform legacy mine systems at a competitive cost.

14. SUBJECT TERMS			**15. NUMBER OF PAGES**
decision support, simulation system, COA development, COA analysis, capability development, counter mobility, USW, MIW, AUWS, UUV, underwater networks, unmanned systems, autonomous systems			169
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500 Standard Form 298 (Rev. 2–89)
Prescribed by ANSI Std. 239–18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

A DECISION SUPPORT SYSTEM FOR EVALUATING SYSTEMS OF UNDERSEA SENSORS AND WEAPONS

Cohort 142O/Team Mental Focus

Submitted in partial fulfillment of the
requirements for the degrees of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

John Glisson Nathan Hagan CDR Robert Patchin, USN

AND

MASTER OF SCIENCE IN ENGINEERING SYSTEMS

Alyson Ledder

from the

NAVAL POSTGRADUATE SCHOOL
December 2015

Lead editor: CDR Robert Patchin, USN

Reviewed by:

Bonnie Young	Paul Shebalin	Richard Williams
Project Advisor	Project Advisor	Second Reader

Accepted by:
Ronald Giachetti
Systems Engineering Department

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This project developed and analyzed the requirements for a decision support system capable of simulating future naval mine warfare scenarios. As the U.S. Navy explores replacing legacy naval mines with new systems of undersea weapons, it requires the supporting tools to evaluate and predict the effectiveness of these system concepts. While current naval minefield modeling and simulation capabilities provide planners with the capability to design and evaluate the effectiveness of minefields using legacy naval mine capabilities, they are not adequate for the planning and performance modeling of new concepts under consideration. The project addressed gaps in the Navy's capability to simulate mine warfare scenarios involving arrays of distributed sensors linked with autonomous mobile weapons by reviewing the current innovations in naval mine warfare development, verifying the gap in current modeling and simulation capabilities, and using systems engineering processes to derive solution requirements. Analysis conducted using prototype simulation capabilities, developed as part of this project, indicates that these future systems will likely outperform legacy mine systems at a competitive cost.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF FIGURES

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

ABM	agent based modeling
AN	ambient noise
ASW	anti-submarine warfare
AUWS	Advanced Undersea Weapon (warfare) System
C2	command and control
CNO	Chief of Naval Operations
COA	course of action
COOP	continuity of operations
CY$	current year dollars
D3A	decide, detect, deliver, assess
DoDAF	Department of Defense Architecture Framework
DRM	design reference mission
EC	expected casualties
EEFBD	enhanced functional flow block diagram
EMI	energy, material and information
FUWS	future undersea weapon system
GAMET	General Analytical Minefield Evaluation Tool
GCCS-M	Global Command and Control System, Maritime
GOTS	government off-the-shelf
GUI	graphical user interface
IETM	interactive electronic technical manual
IPR	in progress review
IS	information system
ISEA	in service engineering agent
JCA	joint capability area
JCIDS	Joint Capabilities Integration and Development System
JFMCC	Joint Force Maritime Component Commander
JROC	Joint Requirements Oversight Council
KPP	key performance parameter
LCC	life cycle cost

LML	Life cycle Modeling Language
LOC	line of communication
MBSE	model-based system engineering
MCM	mine countermeasures
MEDAL	Mine Warfare Decision Aide Library
Mental Focus	Modeling Engagements of Nodal Targeting and Logic: Flexible Options for Continued Undersea Superiority
MFSA	Mental Focus Simulation Application
MIW	mine warfare
MNF	multinational force
MOE	measure of effectiveness
MOP	measure of performance
NAVSEA	Naval Sea Systems Command
NMAWC	Naval Mine and ASW Command
NPS	Naval Postgraduate School
NR KPP	net ready key performance parameter
NTA	naval tactical task
OCS	organized complex systems
OE	operational environment
ONR	Office of Naval Research
P_C	probability of classification given detection
P_d	probability of detection
P_F	probability of engagement (fire) given classification
P_k	probability of kill given engagement
PEO	program executive office
PKI	public key infrastructure
PMS	program manager, NAVSEA
POD	port of departure
QFD	quality function deployment
SE	systems engineering
SEA17B	NPS System Engineering Analysis Cohort 17, Team B
SIT	simple initial threat

SL	signal source level
SME	subject matter expert
SMWDC	Naval Surface and Mine Warfighting Development Center
SVP	sound velocity profile
SysML	Systems Modeling Language
TDD	Target Detection Device
TOPSIS	technique for order of preference by similarity to ideal solution
TRITON	Tactical Relay Information Network
UJT	universal joint task
UJTL	Universal Joint Task List
UNTL	Universal Naval Task List
UML	Unified Modeling Language
USW	undersea warfare
UUV	unmanned undersea vehicle
WSAN	wireless sensor actor network

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

> The main purpose of sensor networks is to utilize the distributed sensing capability provided by tiny, low powered and low-cost devices. (Jamshidi 2009, 20)

In future concepts of undersea warfare, traditional mine warfare systems may be replaced with networks of sensors providing information to mobile, intercept-to-engage weapons. While current naval minefield modeling and simulation capabilities provide planners with the capability to design and evaluate the effectiveness of minefields using legacy naval mine capabilities, they are not adequate for planning and assessing the performance of new concepts under consideration (Ponirakis 2014). The Modeling Engagements of Nodal Targeting And Logic: Flexible Options for Continued Undersea Superiority (Mental Focus) team used systems engineering principles to identify and address this gap in the Navy's ability to predict and evaluate the performance potential of these future mine warfare architectures.

The Mental Focus team identified the system requirements for a simulation system capable of predicting the performance of these future systems and evaluating their mission effectiveness. Appling Model-Based Systems Engineering (MBSE) principles, the team developed a conceptual architecture model and used it to validate the completeness and consistency of proposed top-level requirements. The team used software engineering techniques to develop a prototype simulation system, demonstrating the conceptual solution approach.

Finally, the team used the prototype simulation system to conduct an initial analysis of the potential benefits of future mine warfare architectures. Using the prototype simulation system, the team compared the performance of a legacy mine system and a future undersea weapon system (FUWS) of distributed sensors linked with autonomous mobile weapons. The team's analysis showed that the FUWS could provide improved, sustained performance compared to the legacy mine system. The prototype simulation system showed the threat presented to the enemy by a legacy mine system decayed exponentially as sequential enemy vessels forced a channel through the

minefield. In the scenarios considered, by the sixth transiting vessel less than 20% of the original threat remained, despite the fact that upwards of 90% of the mines remained in the minefield. The FUWS, however, continued to present a significant threat to each vessel transiting the minefield, decaying only as the weapons in the system were exhausted. The increased threat presented by FUWS and its ability to sustain that threat are functions of the FUWS architecture and how it employs a many-to-many relationship between sensors and weapons.

The team contends that the change in the performance characteristics resulting from the change in system architecture warrants a reconsideration of the simple initial threat (SIT) as the principal minefield measure of performance. When both architectures provide similar ranges of initial threats to the first vessel, the sustained capability of the FUWS results in a significantly higher enemy expected casualties (EC).

> With regard to narrow passes, if you can occupy them first, let them be strongly garrisoned and await the advent of the enemy. (Sun Tzu)

ACKNOWLEDGMENTS

We, the students of Systems Engineering Cohort 142O, Team Mental Focus, would like to thank our advisors, Bonnie Young, lecturer in Systems Engineering, and RADM Paul Shebalin, USN (Ret), professor of the Practice of Systems Engineering, for their guidance and patience as our team navigated this project. We are also deeply indebted to RADM Rick Williams, USN (Ret), Expeditionary and Mine Warfare adviser, for his support and guidance, ensuring our project was able to—in at least some small way—contribute to fleet war-fighting capability.

Additionally, we would like to acknowledge the support of our colleague, Tim Wise, for asking critical questions as we formulated the project concept and scope. His thoughtful insight and dedication to understanding the details challenged us to deeper understandings of the problems, tools, and solutions.

Finally, we would like to thank our families for their patience and understanding through the duration of our studies. Without their selfless support, none of this would have been possible.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

> Currently, there are a number of gaps within minefield planning, modeling, and simulation capabilities. With the emergence of new mining technologies, new software methodologies are needed to investigate capabilities, drive new requirements and measures of effectiveness, address training needs, and to meet Navy strategic goals. (Ponirakis 2014)

In U.S. Navy doctrine, mine warfare (MIW) includes both the use of sea mines to project power and shape enemy behavior and the use of various systems and tactics required to defeat and deny the enemy's use of mines. Figure 1 shows this hierarchy, overlapped with the two Joint Capability Areas (JCAs) provided by MIW. Over the past few decades, the Navy has invested significantly more resources in Mine Countermeasures (MCM) as a Force Protection capability than in sea mines as a principal Force Application capability[1] (Committee for Mine Warfare Assessment 2001, 36). Recently, however, the Navy has expressed renewed interest in sea mines as means of Force Application and has begun to explore new concepts of sea mines that leverage recent technological advances (Holmes et al. 2014, 7). This project developed system requirements for the modeling and simulation systems required to support development and employment of these future mining capabilities.

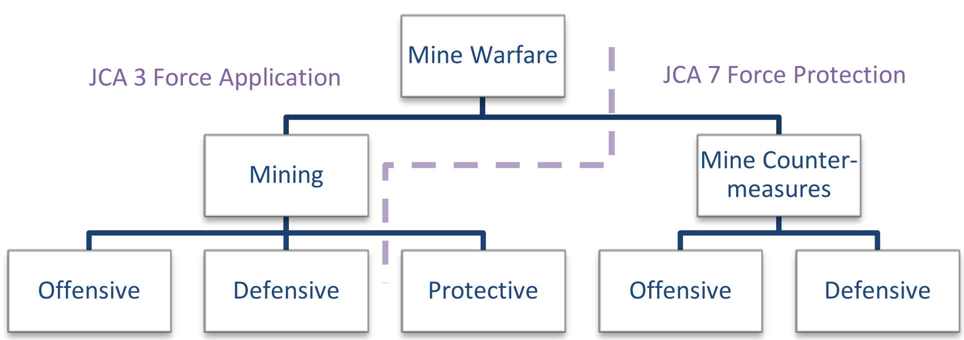


Figure 1. Mine Warfare Hierarchy (adapted from NWP 3-15)

[1] This disparity in focus is not only seen in the allocation of financial resources. The current mine warfare strategic guidance, *21st-Century U.S. Navy Mine Warfare*, dedicates over 95% of the document to MCM capabilities and less than 5% to mining capabilities.

As the Navy explores these new concepts of sea mine capabilities, it requires the supporting tools to evaluate and predict the effectiveness of the concepts. Current naval minefield modeling and simulation capabilities provide planners with the capability to design and evaluate the effectiveness of minefields using legacy naval mine capabilities. These tools, however, are not adequate for the planning and performance modeling of new concepts under consideration (Ponirakis 2014). This report reviews the current status in naval mine warfare development, verifies the gap in modeling and simulation capability, and uses system engineering processes to derive solution requirements. These system requirements are provided to the Navy to inform future capability development efforts.

A. BACKGROUND

> The sea mine was introduced during the American Revolution and the land mine during the American Civil War. Both are products of American ingenuity. In 1970, absent a fitting definition, the National Academy of Sciences' Mine Advisory Committee defined the mine as a "weapon that waits." (Hunt 1998)

From the Bushnell brothers' 1778 attack on the British fleet with kegs of gunpowder fitted with contact fuses (PEO LMW 2009, 3) to the 1991 deployment of Quickstrike[2] mines in the northern Arabian Gulf (6), the sea mine has been the original "long-endurance robotic warrior" (Hunt 1998). Once deployed, the mine "waits" with a degree of autonomy available in few other weapon systems.

As general technological development accelerated in the last 60 years, sea mine technological development has been comparatively stagnant. The last revolutionary advancement in sea mine capabilities was the introduction of the bottom influence mine during World War II; today's legacy mines largely represent 1960s technology (Hunt 1998). As recently as 2009, the Navy's official strategy for naval mining capability development was entirely focused on upgrading the Quickstrike mine with an improved firing mechanism, the Mk 71 Target Detection Device (TDD). While the TDD provided

[2] Originally deployed during the Vietnam War, the aircraft deployed, bottom influence Quickstrike family of naval mines comprises the legacy mining capability of the Navy. The Quickstrike family includes the Mk 62 and Mk 63 converted bombs and the Mk 65 dedicated thin wall mine (PEO LMW 2009, 25).

evolutionary improvements to the sensor, targeting logic, and counter-countermeasures capabilities (PEO LMW, 25–26), it did not fundamentally change the mine's architecture or planning parameters. Sea mines remain fixed, isolated, explode-in-place weapon systems virtually unchanged for over half a century.

The application of recent technological developments in solid-state electronics miniaturization, reliable undersea communication, and new high yield explosive compounds to the naval mining problem has the potential to reinvigorate development of sea mine capabilities and introduce radical changes to the legacy architecture (Hunt 1998). The successor to today's explode-in-place mines will likely rely less on the paired sensor-weapon architecture and more on an array of distributed sensors linked with mobile weapons in a networked architecture. To evaluate and quantify the potential benefits of this radical change in future naval mine system architectures, this project focused on the engineering and conceptual design of a software system capable of modeling these future systems and evaluating their effectiveness.

The Modeling Engagements of Nodal Targeting And Logic: Flexible Options for Continued Undersea Superiority (Mental Focus) Simulation Application (MFSA) provides the user with the ability to determine the effectiveness of planned configurations of sensors and weapons available in a futuristic net-centric naval mine system. Because this technologically advanced architecture provides for new emergent capabilities, the MFSA evaluates new, more complex, measures of effectiveness (MOEs) in addition to the traditional minefield MOEs.

B. FUTURE UNDERSEA WEAPON SYSTEM (FUWS)

> The Advanced Undersea Weapon System (AUWS) is a group of unmanned systems (sensors, effectors, communications, and vehicles) that can be pre-positioned to autonomously and persistently influence the adversary at a time and place of our choosing. (Edwards and Gallagher 2014)

During his 2009 "State of Mine Warfare" annual presentation to the CNO, the Commander Naval Mine and ASW Command (NMAWC), RADM Frank Drennan, coined the concept of Advanced Undersea Weapons System (AUWS). RADM Drennan

noted that naval "mines" should no longer be thought of as dumb, immobile weapons waiting for unsuspecting mariners to run into them; but rather, that existing and developing technologies could transform the historic naval mine into a system of distributed sensors and moveable weapons with vastly improved capability. In 2010–2011 the Naval Postgraduate School System Engineering Analysis Cohort 17, Team B (SEA17B), developed and analyzed AUWS as an alternative concept for providing undersea warfare (USW) dominance (Emmersen et al. 2011, vii). The AUWS concept provides an innovative, flexible, modular system of systems approach to future naval mining capabilities. Because it provides a useful architecture for what a future naval mine system may look like, the Mental Focus project used this future concept, as articulated by SEA17B, as a representative instantiation of a potential future system of systems approach to naval mine warfare. The term AUWS has since been adopted by the Office of Naval Research (ONR) as a particular research and development program (Everhart 2012), the Advanced Undersea Weapon[3] System. Because of the potential ambiguity associated with the AUWS, the Mental Focus project used the umbrella term Future Undersea Weapon System (FUWS) to describe a broad set of possible concepts, including the instantiations of AUWS. This allowed the project to leverage the conceptual approach of SEA17B without being tied to the particular architecture selected by ONR.

As shown in the high-level operational concept (Figure 2), this notional advanced mining system of systems promises increased flexibility, relative to legacy minefields, by employing distributed sensors and modular effectors[4] to generate desired tactical and operational effects. Figure 2 shows a distributed sensor network detecting the presence of a submerged threat target. The sensors communicate the presence of the threat to a weapon, such as the encapsulated torpedo on the right, which then engages the target al.so shown in Figure 2 is a surface warship detected by the distributed sensor network.

[3] Note the change from *warfare* system to *weapon* system. This project used the term *weapon* system to describe a physical system procured and employed to deliver a military capability. The term *warfare* system is used to describe the systematic employment of the art and science of operational warfare.

[4] *Effector* is a term used to describe mines or weapon payloads in the AUWS architecture (SEA17B 2011, 32). This term is used interchangeably with *mine* and *weapon payload* throughout the project.

The system has yet to engage this target, but it may soon direct engagement with the weapons battery in the lower left of the figure when the target meets engagement criteria. While Figure 2 shows a FUWS deployed in a seaport closure scenario, where the operational commander is attempting to deny the enemy access to and from their own seaport (offensive mining), the FUWS concept may also be used to influence enemy operational behavior in the defense of friendly seaports (protective mining) as well as in open-ocean, area-denial scenarios (defensive mining).

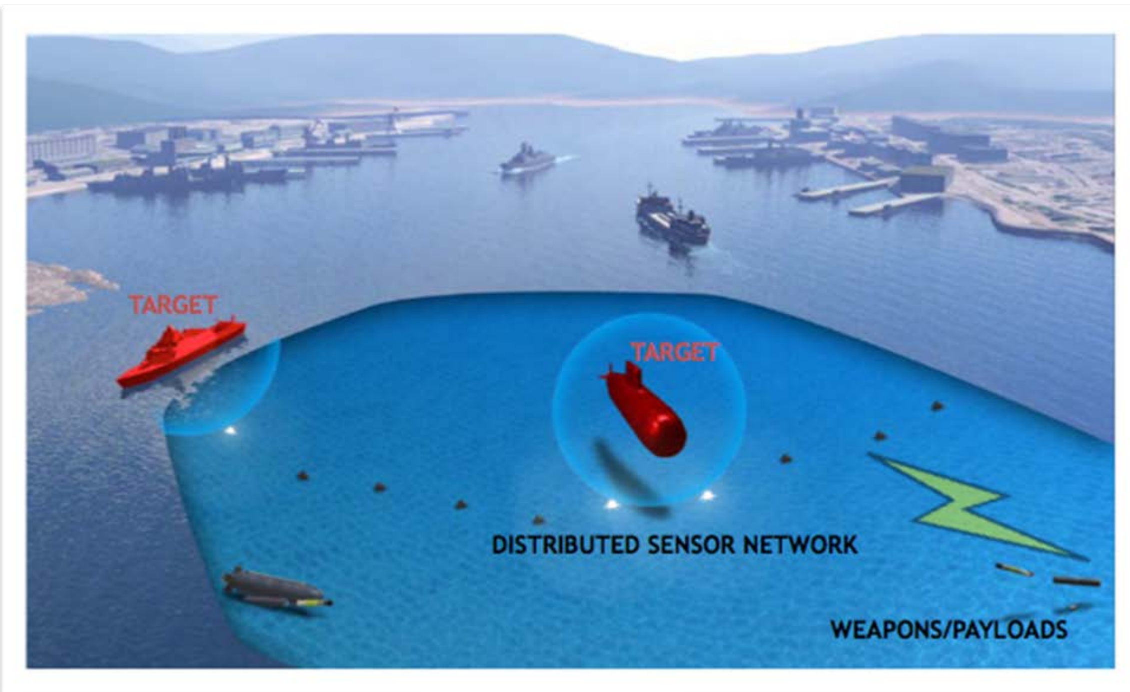


Figure 2. FUWS Operational Concept (adapted from Everhart 2012)

C. CAPABILITY GAP

> Capability Gap—The inability to meet or exceed a capability requirement, resulting in an associated operational risk until closed or mitigated. The gap may be the result of no fielded capability, lack of proficiency or sufficiency in a fielded capability solution, or the need to replace a fielded capability solution to prevent a future gap. (CJCSI 3170.01I 2015)

There are a variety of potential FUWS weapons configurations that leverage existing and/or developmental technologies varying in size, cost, complexity, lethality,

range, and speed. In some scenarios, it may be necessary to increase weapon quantity, with range and lethality being less important. While in other scenarios, a larger explosive charge in combination with increased range and speed may be more likely to produce the required effects. Each weapon payload has different performance characteristics, which will allow the overall system of systems to be tailored for a particular desired mission outcome.

In order to develop and employ such systems in an effective manner, the Navy requires a decision-support simulation system that accurately models the detection of a target, decision logic, communication of target parameters, and engagement of the target with a selected weapon.[5] Without establishing a properly abstracted simulation system architecture, it will be difficult to establish realistic decision-support system-level performance requirements and the associated subsystem allocated requirements. Additionally, operational planners need the ability to develop mine employment plans and accurately predict the effectiveness of planned configurations of weapons and sensors.

D. PROJECT SCOPE

The project scope was based on addressing this gap in mine simulation and planning capability using available resources. The MFSA high-level operational concept (Figure 3) provides a graphical representation of the MFSA in operation.

The MFSA system provides warfare center program analysts and capability developers the ability to understand and optimize the effectiveness of a particular configuration, supporting alternative analysis and informing capability development. The MFSA also provides minefield planners at reach-back support commands the ability to optimize the effectiveness of a particular configuration, supporting operational decisions and tactical system deployment.

However, because the project was not resourced to deliver a mature, fully functional, and integrated decision support system, the Mental Focus team focused efforts

[5] The applicable required JCA is 5.3.5 *Analyze Courses of Action*: The ability to evaluate potential solutions to determine likelihood of success.

on MFSA requirement analysis and architecture development. The project team used a prime directive statement to ensure efforts remained focused on the MFSA statement of need, project goals to communicate the desired project end state, and a prototype simulation system to visualize and demonstrate the system requirements and architecture.

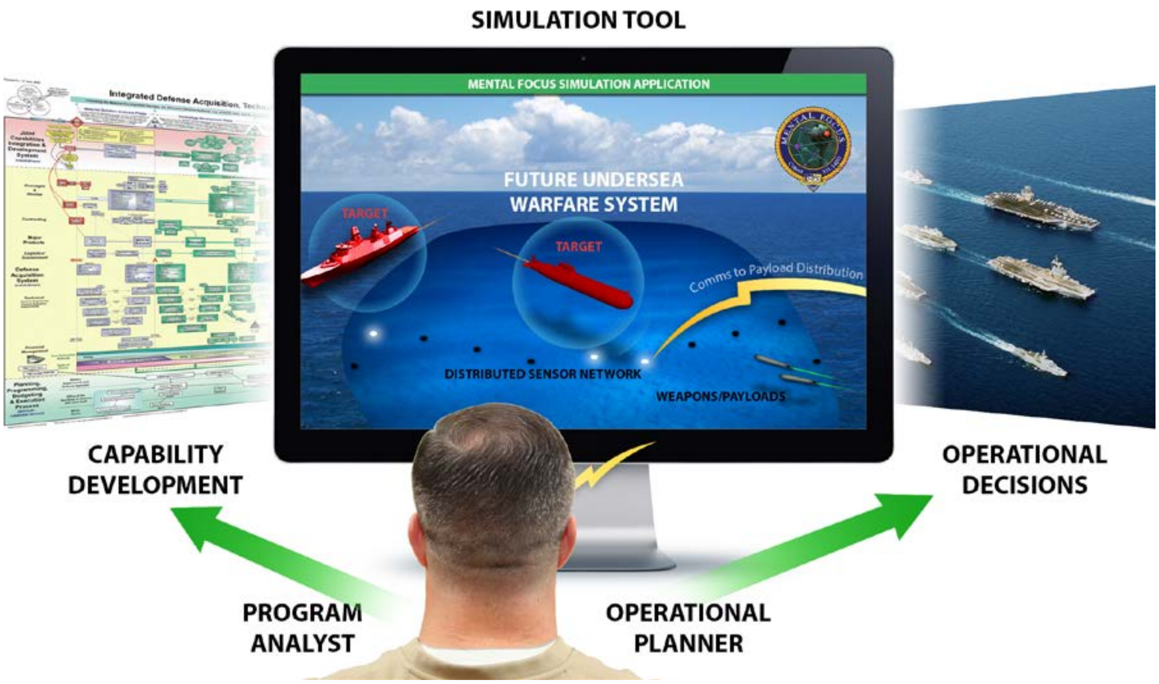


Figure 3. MFSA Operational View (OV-1)

During the literature review, the project team determined that most current efforts in the AUWS concept development have been directed at analyzing the required sensor systems and that significantly less effort was being focused on the required weapon system components. By focusing on the weapons portion of the FUWS concept, the analytic efforts of the Mental Focus project contribute to capability developer understanding at stakeholder organizations. This helps to shape the U.S. Navy's future undersea warfare capabilities and directly supports the Chief of Naval Operations' (CNO's) vision of continued undersea dominance (Greenert 2011, 2).

MFSA will provide stakeholders with the ability to evaluate alternative FUWS configurations in various mission scenarios and optimize the system performance to

achieve desired operational effectiveness. Capability developers may use the tool to evaluate alternative tactics and materiel components, support development of future undersea weapon systems and inform development priorities.

1. System Context and Prime Directive

As shown in the MFSA context diagram (Figure 4), the project focused on the requirements of the proposed simulation application. The system uses information about the available FUWS component architecture, information about the environment, and information about the intended mission employment to provide an optimized deployment configuration. The system interfaces with various users including analysts, maintainers, and operational decision makers.

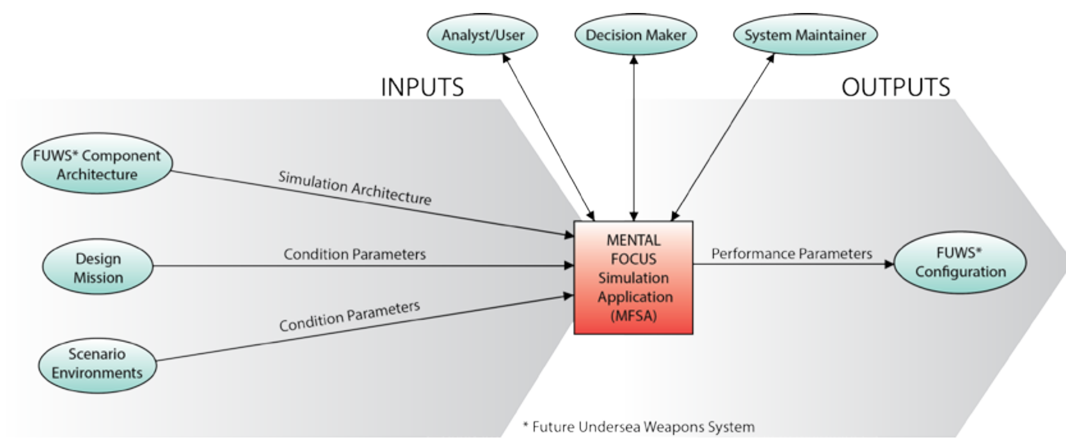


Figure 4. MFSA Context Diagram

To keep the project efforts focused on the required system capability, the team developed the following high-level statement of purpose, or prime directive:

> Analyze and compare system configurations[6] to inform the development and employment[7] of distributed sensors and networked effectors in the undersea environment.[8]

[6] Applicable Universal Joint Tasks (UJTs) are *Analyze Courses of Action* (OP 5.3.5) and *Compare Courses of Action* (OP 5.3.6).

[7] Applicable UJT is *Tailor Forces* (ST 7.1.3).

[8] Applicable Universal Naval Task is *Plan Minefields* (NTA 1.4.1.1).

This directive was useful in developing the project study questions and goals and in communicating the purpose of the proposed MFSA system and the required simulation capability. The team found the use of a prime directive statement useful in focusing project efforts and minimizing distractions outside the MFSA scope. By mapping the prime directive to appropriate joint and service tasks, the team ensured traceability and alignment with stakeholder organizational goals.

2. Study Questions

The following study questions were used to guide the project efforts:

1. What capabilities does a networked sensor-weapon system provide over the existing legacy mine capability?
2. What emergent behavior results from modular networks of sensors and weapons?
3. What are the necessary sequences of events that must be modeled in a FUWS architecture to simulate mission scenarios?
4. What parts, if any, of existing models or simulation systems for undersea warfare could be reused or integrated into MFSA?

3. Goals and Objectives

The following project team goals and objectives were used to scope project stakeholder expectations and define the anticipated project end state. They represent the level of MFSA development the team anticipated available resources could support.

1. Apply Model-Based Systems Engineering (MBSE) principles to the development of the MFSA architecture conceptual design.
2. Identify requirements for the MFSA conceptual architecture.
3. Develop model(s) that represent the sequence of targeting and decision events in a mining scenario from sensing the presence of a vessel to engaging a threat.
4. Develop a prototype simulation system to demonstrate the conceptual architecture and to support requirement discovery.
5. Investigate which measures of effectiveness are most applicable for evaluating advanced undersea weapons systems.

4. Assumptions & Constraints

The following assumptions and constraints were explicitly identified in the scoping of the project:

1. The SEA17B AUWS concept is just one possible instantiation of a future system. MFSA must be applicable to other potential systems as well.
2. All data required as inputs for the decision support system already exists and is accessible by government personnel and/or systems with proper security clearances.
3. Current commercial-off-the-shelf desktop computers provide sufficient computational processing power for use by the decision support system.
4. The consideration of potential future weapon system components can be limited to currently fielded technologies and to technologies that can be realistically fielded within the next 10 years.
5. The MFSA requirement development process would remain solution neutral. While the MFSA capability may be affordability implemented by upgrading or modifying an existing system, the project would not assume this.
6. The development of a demonstration system would be constrained by the team's limited resources, including limited software programming experience.

E. APPROACH AND METHODOLOGY

By clearly articulating the value of networked sensor-weapon system over the existing legacy capabilities, this project enhanced the Navy's knowledge of persistent undersea warfare. This section describes the approach and methodology that the project team took as a means to accomplish the goals, meet the objectives and achieve the desired benefits of the project.

1. Project Process

Figure 5 shows the simulation system development process used by the Mental Focus team.

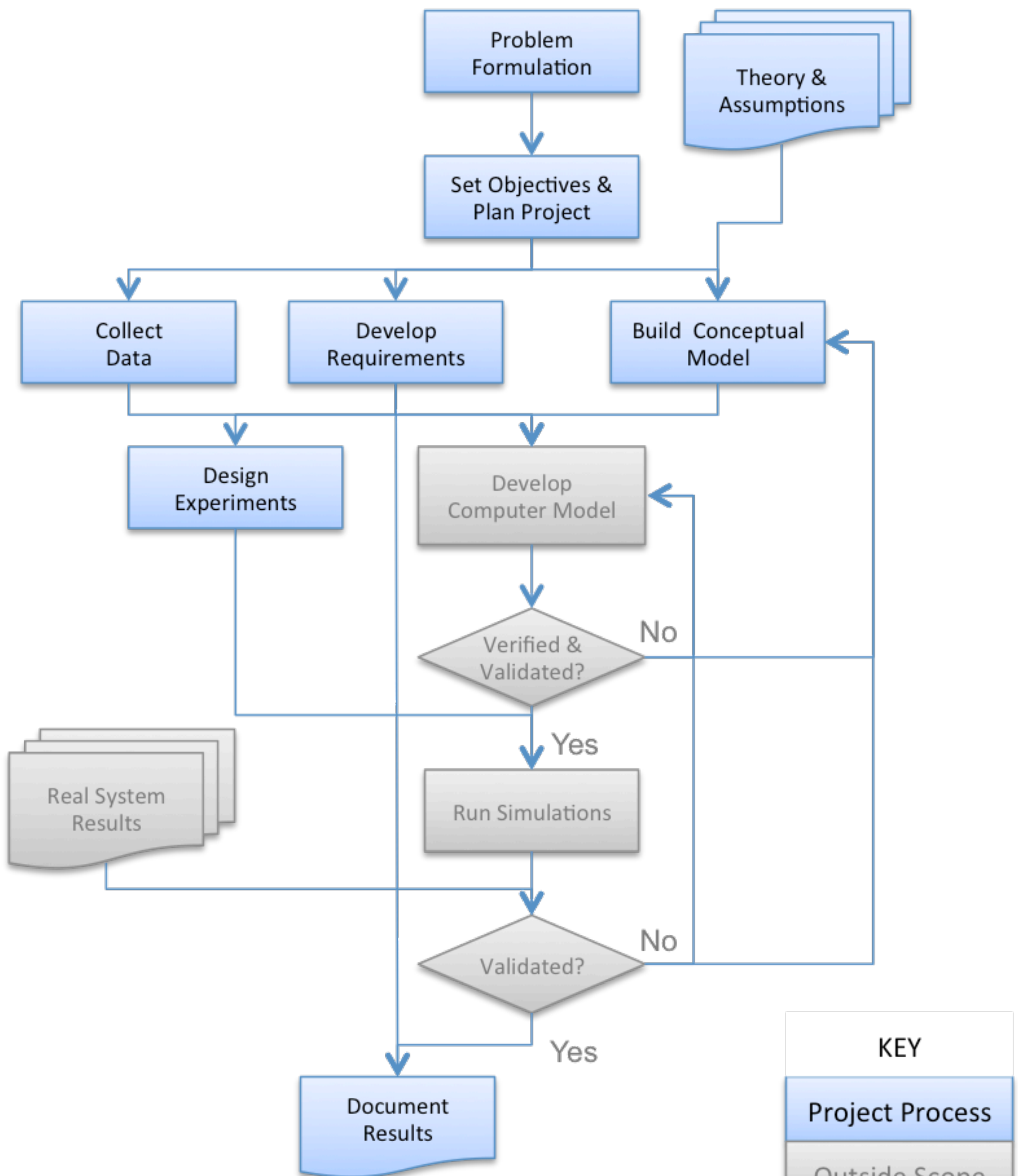


Figure 5. Project Process Map (adapted from Heath et al. 2009)

Adapted from process maps used for simulation system development, this process highlights the steps conducted as part of this project. With limited project resources, the team chose to focus on development of system requirements and supporting conceptual model. This report provides documentation of the project team's efforts and is provided to support execution of the remainder of the development process.

2. Team Organization

The Mental Focus project team was composed of four Naval Postgraduate School graduate students, identified in Table 1, guided by two faculty advisors. The team included members of diverse backgrounds, but all with experience in the development and application of naval warfare systems. The team also had significant background experience and interest in the undersea domain.

Table 1. Team Mental Focus

Team Member	Prior Degree	Command/Employment
John Glisson	VA Tech, BSME '05	Assistant Program Manager, Mine Warfare Program Office (PMS 495)
Nathan Hagan	Webb Inst, BS NAME '12	Naval Architect for the Structural Criteria and Risk Assessment Branch, Naval Surface Warfare Center, Carderock Division, West Bethesda
Alyson Ledder	Temple, BBA Econ '10	Program Analyst providing contractor support to Submarine Mast Mechanical System ISEA at Naval Surface Warfare Center, Philadelphia
Robert Patchin	Gonzaga, BSME '99	Submarine Warfare officer assigned to the Joint Staff J8 as an analyst supporting the Force Support Functional Capabilities Board

In order to provide structure and accountability, specific team roles and responsibilities were identified for each team member, shown in Table 2, as part of the project planning process. These team assignments were selected to leverage individual expertise and skills as well as team member interests. To ensure equitable participation with the small team size, each team member also participated in every aspect of the project development and execution.

Table 2. Team Roles and Responsibilities

Team Member	Role	Responsibilities:
John Glisson	System Architect	Coordinated system architecture design and development Conducted technical briefings
Nathan Hagan	Team Lead	Conducted team meetings Tracked project deliverables and schedule progress Updated and liaised with stakeholders and advisors Identified and assigned additional duties as required
Alyson Ledder	Modeling Lead	Selected Modeling and Simulation tools and methods Coordinated Modeling and Simulation efforts and analysis
Robert Patchin	Editor and Programmer	Coordinated final editing and submitted team reports Programmed prototype simulation system

3. Literature Review

Early in the project, the team conducted a thorough literature review focused on establishing a baseline understanding of the current strategic, programmatic, and academic efforts in development of persistent, distributed undersea weapon systems. The project team also reviewed the modeling and theory of wide-area sensor networks and targeting-decision logic. These reviews of prior work helped establish the project team's subject matter knowledge base and ensured the relevance of the project goals to current efforts.

While many of the sources reviewed are included in the list of references, the project team felt it beneficial to highlight the following sources, as they contributed significantly to the MFSA development:

- Emmersen, Tracy, Ng Kiang Chuan, David Chiam, Ong Zi Xuan, Perh Hong Yih Daniel, Koh Wee Yung, Wes Wessner, et al. 2011. "Advanced Undersea Warfare Systems." Master's thesis, Naval Postgraduate School. http://hdl.handle.net/10945/6959.

  This Naval Postgraduate School (NPS) Systems Engineering capstone project focused on design of an advanced undersea warfare system architecture, shaping much of the current AUWS developmental efforts. The functional decompositions

and dendritic models provided useful architectures for understanding the AUWS concept. Mental Focus built on this project by modeling combinations of sensors and actors (weapons). Specifically, MFSA provides the tool necessary to optimize the system architecture (69–70) for a variety of design reference missions (DRMs).

- Bard, William. 2013. "Naval Minefield Modeling and Simulation: An Examination of General Analytical Minefield Tool (GAMET) and Other Minefield Models." Naval Postgraduate School.

  This NPS Operations Research master's thesis examined a government off-the-shelf (GOTS) tool for calculation of minefield system effectiveness. William Bard's thesis provided a valuable source for the team's understanding of current minefield simulation capabilities. His description of functionality and capability of GAMET (17–22) provided a foundation for much of the project's capability gap analysis and capability development efforts.

4. Methods

The project team recognized that successful development of the MFSA system would involve not only general systems engineering (SE) practices, but also Model-Based Systems Engineering (MBSE) and software engineering methodologies. As shown in Figure 6, the successful conceptual design development of MFSA was accomplished using an integrated interdisciplinary approach. The methodologies and approaches leveraged from each discipline are shown in Table 3. The selected methods support a holistic evolutionary process model for MFSA software development. The team's early inclusion of software engineering methods, including the development of a prototype system to support refinement of requirements, was intended to support rapid transition to MFSA development. Within the talents and resources available to the team, the team developed a demonstration prototype, simulating the first sprint in a scrum development effort (Pressman 2015, 79).

Table 3. Methods Employed by the Mental Focus Project

Discipline	Method
SE	Consultations with Subject Matter Experts (SMEs) to understand stakeholders needs and concerns
SE	Determination of Key Performance Parameter (KPP) requirements
SE	Determination of the evaluation and extension of the Measures of Performance (MOP) of a FUWS
SE	Performance of a Quality Function Deployment (QFD) analysis to select the prototype simulation platform
MBSE	Determination of MFSA system architecture and targeting logic requirements using MBSE principles
MBSE	Development of a conceptual system architecture expressed in Unified Modeling Language (UML) and DOD Architecture Framework (DoDAF) products
Software Engineering	Definition of use case scenarios typical of the operational environment
Software Engineering	Agile development of a system demonstration prototype

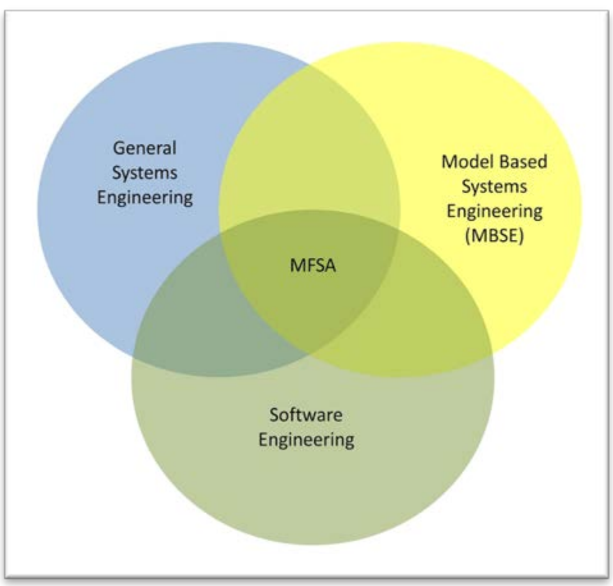


Figure 6. Integrated Interdisciplinary Approach to MFSA Development

THIS PAGE INTENTIONALLY LEFT BLANK

II. CAPABILITY GAP ANALYSIS

> Mining is: … In naval mine warfare, an explosive device laid in the water with the intention of damaging or sinking ships or of deterring shipping from entering an area. The term does not include devices attached to the bottoms of ships or to harbor installations by personnel operating underwater, nor does it include devices that explode immediately on expiration of a predetermined time after laying. (UJTL 2015, TA 1.4)

This chapter presents the Mental Focus team's analysis of the system need. The team identified and categorized capability stakeholders to ensure the needs of the customer informed the team's perspective on capability requirements. The team then scoped the requirements for modeling potential FUWS architectures by conducting a review of potential architectures. Finally, the team scoped the capability gap MFSA attempts to close by identifying the shortfalls in current simulation systems.

A. STAKEHOLDER IDENTIFICATION

The Mental Focus team identified a number of active stakeholders, those that would have a direct interest in the team's project, and passive stakeholders, those that would have interest in the future development of the proposed system. These stakeholders, shown in Tables 4 and 5, respectively, were initially identified during the proposal development phase to assist the team in identifying the customer need for FUWS simulation capabilities. Their roles and anticipated concern or interest with the proposed capability development were further refined during the project stakeholder analysis.

The Mental Focus team identified four active stakeholder organizations that formed the principal customer base for the MFSA project. The missions and viewpoints of these organizations, as articulated in Table 4, were considered throughout the project execution. These organizations are all actively involved in the research and development of AUWS, and have established much of the critical background information necessary for the teams understanding of future mining capabilities. Additionally, as the NPS Expeditionary and Mine Warfare Adviser, Rear Admiral (ret) Rick Williams was able to validate the MFSA capability gap and problem statement.

Table 4. Active MFSA Stakeholders

Stakeholder	Roles and Anticipated Concerns
Office of Naval Research (ONR)	Project Customer: Needs to understand capability and performance of various FUWS concepts in a range of missions and environments Concerned with technological challenges and development of next generation naval weapon systems
Naval Sea Systems (NAVSEA) including the applicable Program Executive Office (PEO) and supporting program offices	Identified as MFSA *system developer* end user organization Project Customer: Needs to understand capability and performance requirements of various FUWS concepts in a range of missions and environments Concerned with efficient use of resources to support the research, development, acquisition, and modernization of naval weapon system capabilities
Naval Surface and Mine Warfighting Development Center (SMWDC)	Identified as MFSA *operational planner* end user organization Project Customer: Articulates mine warfare capabilities requirements; promotes rapid delivery of new technologies; provides minefield planning capabilities to operational forces Concerned with operational employment of mine warfare capabilities and mine warfare mission performance metrics
Naval Postgraduate School (NPS) Faculty	Project Governance: Ensures project meets standards of academic excellence Concerned with increasing combat effectiveness of naval services

The team also identified a number of passive stakeholder organizations with future roles in the development and employment of MFSA. The missions and viewpoints of these stakeholders, identified in Table 5, were also considered throughout the project execution. While not directly involved as the system customers, their role in resourcing and integrating the MFSA system and in implementing recommended FUWS concepts will be critical to the ultimate goal of improving warfighter combat effectiveness. During MFSA development, these stakeholders were considered primarily from their role in the

development and delivery of a FUWS informed by MFSA. Their interests and concerns were used to validate the MFSA output requirements.

Table 5. Passive MFSA Stakeholders

Stakeholder	Role and Anticipated Concern/Interest
Joint Requirements Oversight Council (JROC)	FUWS Governance: Validates joint weapon system requirements Interested in efforts to exploit autonomy in the development of future weapon systems Concerned with risk to mission and affordability
OPNAV N9/N95	FUWS Governance: Manages system requirements of naval warfare systems and assigns resources for system capability development and maintenance Concerned with risk to mission and affordability
Commander Submarine Forces	FUWS Influencer: Leads efforts to sustain advantages in undersea warfare Concerned with undersea warfare readiness
Military-Industrial Complex	FUWS Provider: Builds and delivers undersea weapon systems Concerned with solution development and profitability
Joint Force Maritime Component Commander (JFMCC) and Staff	FUWS Integrator: Establishes undersea warfare goals and priorities Concerned with the ability to project power from the Sea and optimizing employment of assigned assets
Undersea Warfare Commander and Staff	FUWS Integrator: Directs use of undersea systems in the operational theater Concerned with flexibility, mission effectiveness, and probability of kill

B. FUWS ARCHITECTURE REVIEW

> The greatest warfighting return will be generated by proper investment in future USW[9] payloads. The attributes that will provide that return are *endurance* and *autonomy*. (emphasis added, Connor 2013)

To support the required simulation of future mining systems, the Mental Focus team needed to understand the key elements of an advanced mining architecture. To this end, the team extensively leveraged the SEA17B NPS capstone project, "Advanced Undersea Weapons System" (Emmersen et al., 2011). In comparison with the ONR AUWS architecture under development, the SEA17B architecture provides a more academic, solution neutral architecture at the unclassified level. As such, the project team used the SEA17B architecture as the foundation for a robust, accessible FUWS architecture at an appropriate level of abstraction to support MFSA requirement analysis.

1. Functional Context

Consistent with the project's scope and operational concept (Figure 3), the Mental Focus team used the FUWS functional context to describe the level of abstraction required for modeling by the MFSA system. Specifically, in order to inform development priorities and predict operational effectiveness, MFSA must model the FUWS functional behavior as well as the relevant energy, material and information (EMI) interfaces. Modeling at a less detailed level of abstraction, such as the inclusion of FUWS capabilities in a campaign level model, or at more detailed levels, such as the physics modeling of hydro-acoustic transmission, would be outside the identified capability gap and intended MFSA scope.

As seen in Figure 7, the functional context established by SEA17B used four principal groupings of EMI interfaces.

- Controllable Inputs: those inputs and triggers that can be controlled either by the system developer or operational user.
- Uncontrollable Inputs: those inputs and triggers that are part of the undersea environment or are controlled by the enemy.

[9] In U.S. Navy Doctrine undersea warfare (USW) includes mine warfare, submarine warfare, and anti-submarine warfare.

- Intended Outputs: those outputs required by the operational user and designed by the system developer.
- Byproducts: those emergent outputs resulting from the system behavior that must be mitigated (undesirable to the customer) or could exploited (desirable to the customer).

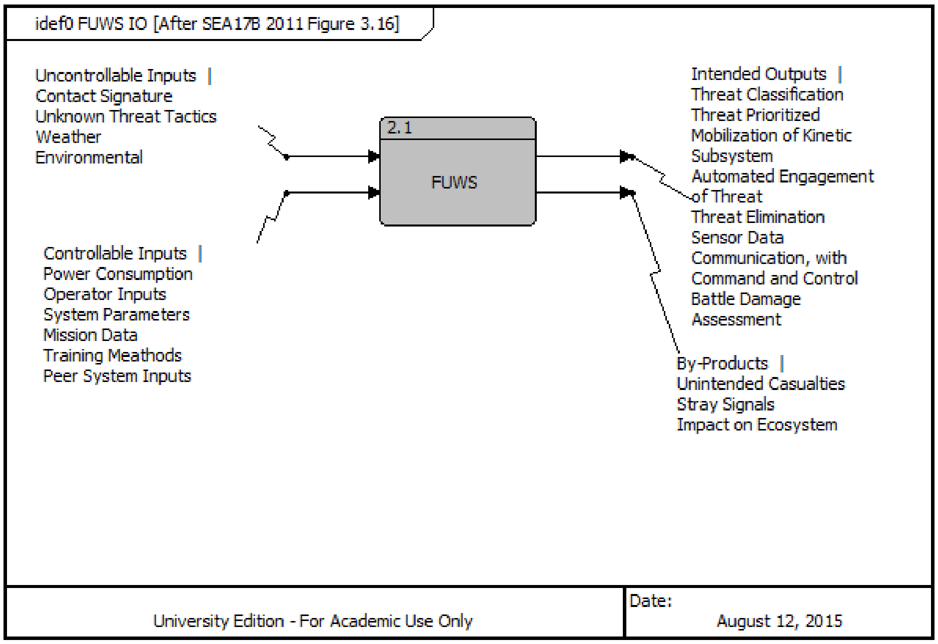


Figure 7. FUWS Functional Context (adapted from SEA17B 2011)

These inputs and outputs, and the associated EMI interfaces, were reviewed by the team and considered for modeling in MFSA. Those inputs required to support the FUWS targeting logic and those outputs required to support identified measures of effectiveness (MOEs) were prioritized for modeling in MFSA as detailed in Chapter III. The remaining inputs, outputs, and byproducts should be considered in enhancing the MFSA utility, but they were not considered as customer requirements based on the identified stakeholders.

2. Functional Architecture

Having bounded the modeling problem with the FUWS functional context, the team needed to understand and define the functional behavior occurring within the FUWS system boundary. Again, by leveraging the SEA17B project's functional

decomposition, the Mental Focus team was able was able to develop a solid understanding of the required functional flow of a FUWS. Figure 8 provides the SEA17B Enhanced Functional Flow Block Diagram (EEFBD) showing the high level, architectural functions performed by FUWS. Of note, the system is responsible for performing a variety of functions simultaneously, independent of the presence of a threat.

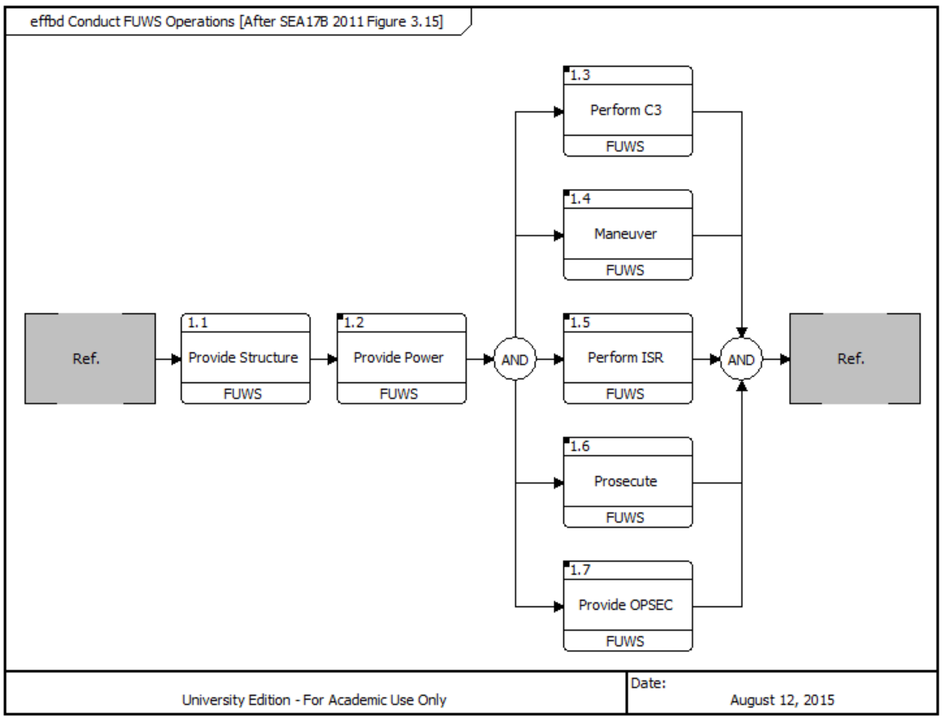


Figure 8. FUWS High Level EFFBD (adapted from SEA17B 2011)

The Mental Focus team also conducted a parallel review of the Universal Joint Task List (UJTL) and Universal Naval Task List (UNTL) to establish traceability of FUWS capabilities to mission requirements (Appendix A). As a result of this review, the team identified the top-level functional requirement of a FUWS as Naval Tactical Task (NTA) 1.4, Conduct Counter-mobility. When decomposing “Conduct FUWS operations” in light of this tie to counter-mobility, the team generated an alternative top-level functional architecture (Figure 9) focused on describing the functions required to conduct counter-mobility. In this decomposition, the FUWS collects information from the environment and threat, the uncontrollable inputs of the functional context. This

information then feeds the execution of internal command and control functions as well as possible coordination with external systems. The rule sets that drive these command, control and communication functions are based on the *controllable inputs* in functional context. When the predetermined engagement logic directs, the FUWS engages a threat to limit its mobility on or below the sea. The loops in this decomposition show the highly iterative nature of the system's operational activities. Because it focused on decomposing the military task to demonstrate the system's functionality, the team adopted this alternative functional decomposition for use in MFSA modeling.

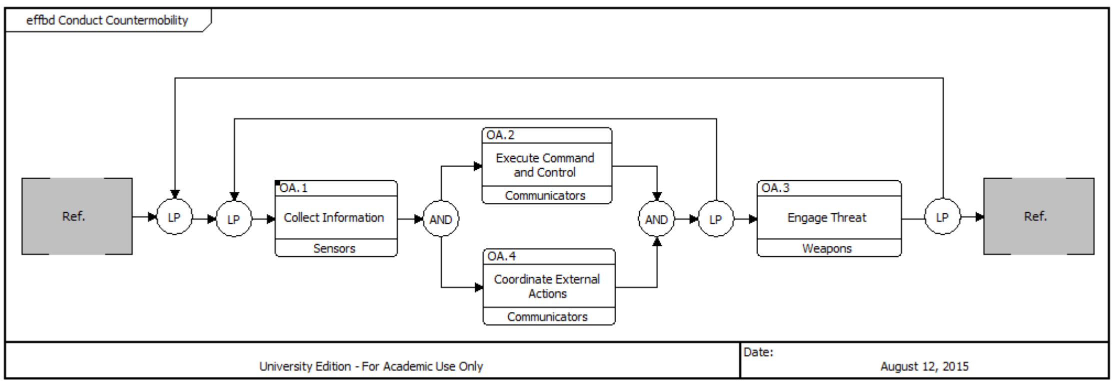


Figure 9. FUWS Conduct Counter-mobility EFFBD

3. Functional Allocation

With the modified understanding of the FUWS functional decomposition, the Mental Focus team proceeded to examine the functional allocation to component subsystems at the top-level architecture. These subsystems and their interactions will form the basis for modeling in MFSA.

As seen in Figure 10, the SEA17B project identified three top-level subsystems. These subsystems can be mapped to the functions identified in Figure 9 and were accepted by the Mental Focus team as an appropriate physical decomposition of a generic FUWS, suitable for modeling in MFSA.

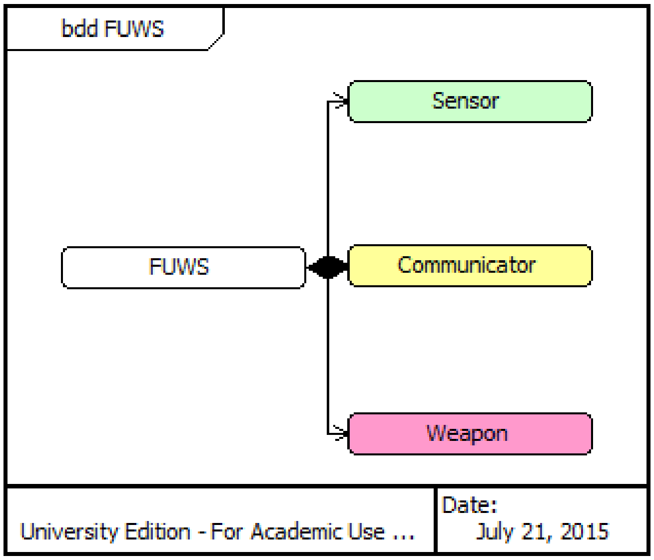


Figure 10. FUWS High Level Decomposition

In order to understand the functional limitations of each subsystem, the SEA17B cohort decomposed these subsystems into technologies based on the physical phenomena exploited in various solution sets. The Mental Focus team began with the SEA17B decomposition, but winnowed down the list of technologies considered based on those with to the greatest congruence with mission requirements and highest technological readiness. The challenges and opportunities associated with each of these technologies must be considered by MFSA

a. Sensors

The FUWS sensors must be capable of collecting information from the threat transmitted through the undersea environment. These sensors must leverage phenomena that could be used to detect and classify the presence of a threat. The Mental Focus team assessed that acoustic (both passive and active), magnetic, pressure and seismic sensors (Figure 11) provided the most mature technologies and most realistic sensor sets for use the FUWS. As such, their employment in sensor network(s) must be capable of modeling by MFSA. The team considered the use of optical sensors but considered the ranges associated with the transmission of photic energy through seawater as limiting and excluded optical sensors from the MFSA requirement.

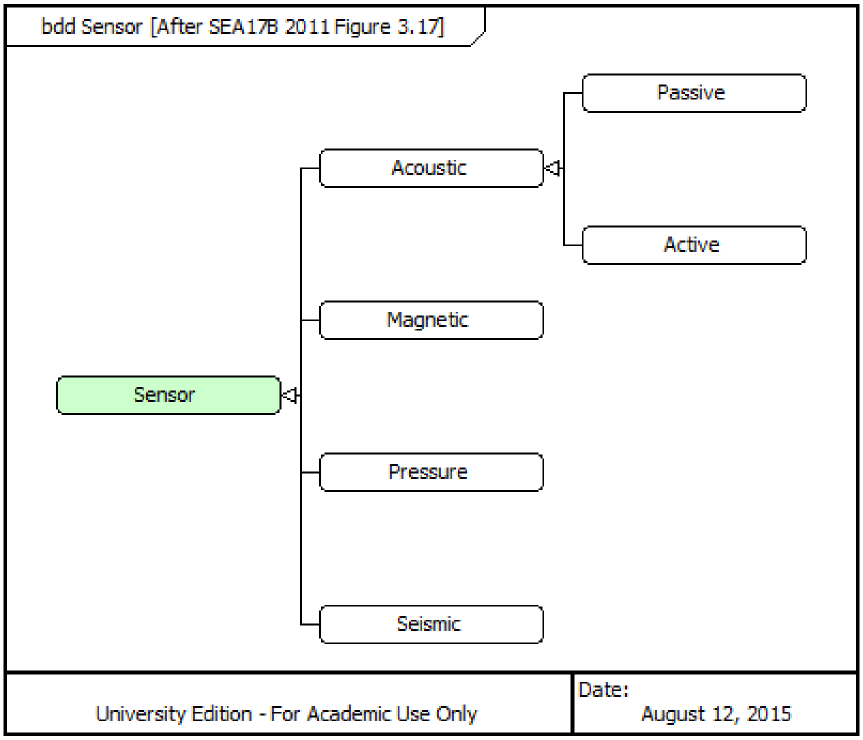


Figure 11. Possible FUWS Sensor Technologies (adapted from SEA17B 2011)

b. Communicators

The FUWS communicators must be capable of transmitting data through the undersea environment from the sensors to the weapons. Additionally, because the command and control functions used to make engagement decisions must happen between the sensor and weapon, these functions were assigned to the communicators. The limiting technological challenge of transmitting data through the undersea environment was used to categorize the possible communicator technologies (Figure 12).

The Mental Focus team assessed that acoustic (digital and analogue) and radio buoy (line-of-sight and satellite relay) communications provided the most mature technologies and realistic communicators. The team also considered the possible introduction of future laser communications as a possible solution based on Defense Advanced Research Projects Agency (DARPA) Tactical Relay Information Network (TRITON) efforts in developing undersea blue laser communications. Finally, the team

included connected communications (fiber-optic and conductive wire) as a possible solution, particularly in protective mining scenarios. The team excluded physical messengers from consideration based on the speed of communications required to engage moving targets and the energy required for supersonic undersea transit.

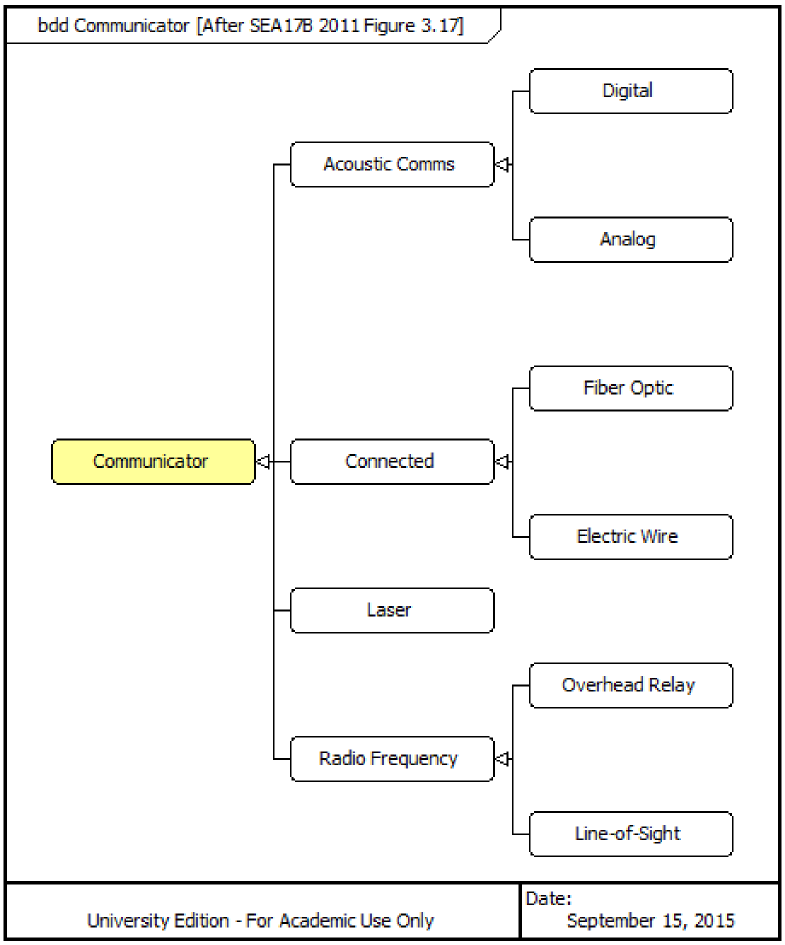


Figure 12. Possible FUWS Communicator Technologies (adapted from SEA17B 2011)

c. Weapons

FUWS weapons must be capable of intercepting and limiting the mobility of an identified threat, using information passed by the communicators. Possible weapon categories broadly include kinetic and non-kinetic. Kinetic weapons rely on physical force, normally associated with an explosive blast, to damage the target. These weapons

include both fixed (similar to current mines) and mobile (similar to current torpedoes) explosive charges. The alternative kinetic weapons in the SEA17B decomposition are indistinguishable from these broad categories. For example, the embedded warhead in an undersea vehicle is effectively a slow speed torpedo. Non-kinetic options, identified as soft kill weapons in the SEA17B decomposition, would include alternative mechanisms, such as use of the electro-magnetic spectrum, to disable threats and counter their movement through the mined area. The revised categorical decomposition of possible weapon classifications is shown in Figure 13.

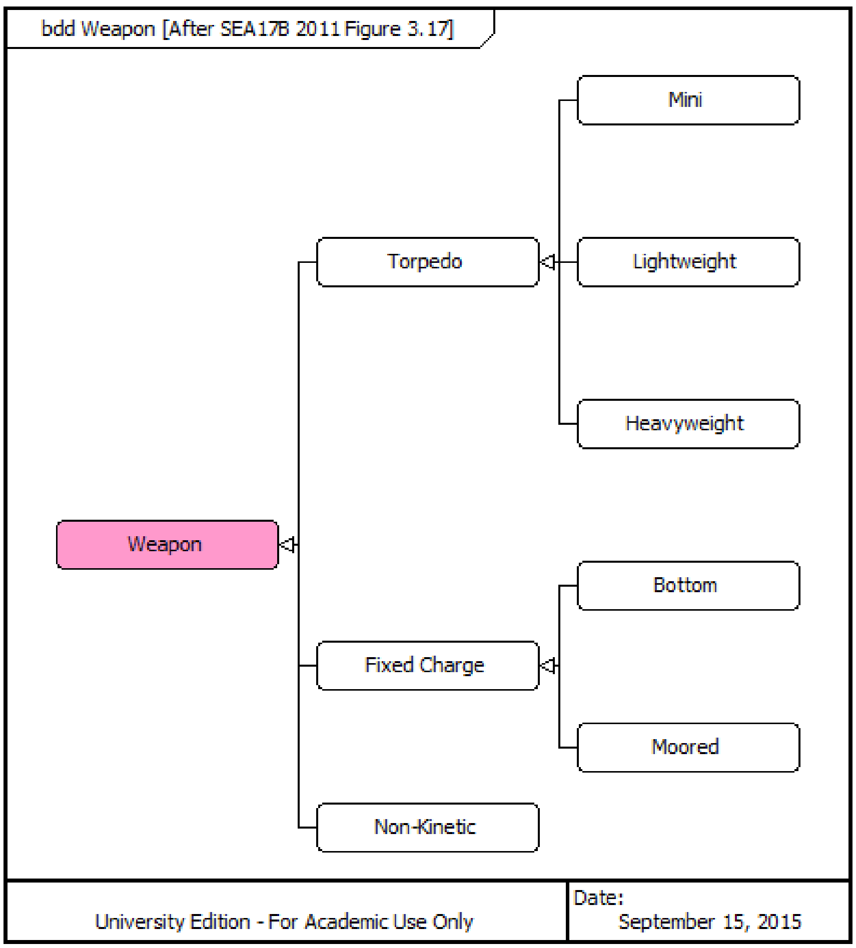


Figure 13. Possible FUWS Weapon Classifications (adapted from SEA17B 2011)

C. EXISTING CAPABILITY REVIEW

The Mental Focus team leveraged William Bard's NPS thesis, "Naval Minefield Modeling and Simulation: An Examination of General Analytical Minefield Evaluation Tool (GAMET) and other Minefield Models," as an analysis of alternatives of current minefield simulation capabilities. Bard concludes that GAMET provides the most effective and capable system currently available for future mining concepts such as FUWS (2013, 53–54). The team accepted this conclusion, limiting the team's review of existing capability to the GAMET system.

GAMET provides "an object-oriented, event-driven simulation used in the evaluation of minefield effectiveness, system performance trade-offs and transitor vulnerability" (Belton 2015, 2). It was initially developed in 1998, predating the development of the AUWS concept. While subsequent GAMET version releases have incorporated some ability to simulate a "networked field of cooperative sensor, relays and remote weapons" (Belton 2015, 4), the capability provided by GAMET remains limited and incomplete. MFSA will address these gaps. Additionally, because of GAMET's established pedigree, the team identified a number of GAMET system components that could be incorporated in an evolutionary development of MFSA. Chapter V.D provides more details.

1. Output Limitations

Perhaps its most significant limitation is the paucity of outputs generated by GAMET, specifically the limited types of minefield MOPs. GAMET is capable of predicting two types of MOPs for a given scenario simulation, the simple initial threat (SIT) and the expected casualties (EC). The SIT is an estimate of the threat presented by the minefield to the first transiting target vessel, expressed as the probability that the threat is prevented from transiting the minefield. The EC is the expected value (mean) number of target vessels prevented from transiting the minefield in a given scenario (Belton 2015, 16).

While these simple MOEs may be adequate for comparison of legacy, explode-in-place, minefield configurations they fail to adequately highlight the potential emergent

capabilities of a networked and mobile FUWS architecture. For example, the decay profile of the minefield threat presented to the n^{th} target vessel could vary dramatically between a legacy minefield and various FUWS architectures. Without understanding this risk profile, the system developers will not understand the impacts of trade space in a FUWS architecture and operational planners will not properly optimize the employment of FUWS capabilities.

This lack of a more robust set of MOEs is indicative of an enterprise-wide shortfall in doctrinal minefield MOEs. Given the demonstrated lack of attention to mining capability development, this may not be particularly surprising. However, with the current resurgence of interest in mining capabilities and development work on AUWS, relevant MOEs for distributed, networked minefields must be developed to support comparative analysis. Simulation systems must be capable of predicting these MOEs to support optimal system development and employment. To support this effort and define relevant MFSA output requirements, the project team developed a number of proposed FUWS MOEs (see Chapter III.C.3). MFSA must be capable of outputting new MOEs identified as relevant in the development and employment of FUWS architectures.

2. Architecture Limitations

The upgrades to GAMET that enable simulation of FUWS only allow for limited FUWS architectures. Specifically, the upgrades were biased toward modeling sensors and communicators and less focused on modeling enhanced weapon components. For instance, while GAMET allows the system user to mix different communicators (modem types) in a scenario, the user may only use a single weapon type in the scenario and the system does not simulate different characteristics associated with various weapon types (Belton 2015, 7). Additionally, GAMET does not consider many of the probabilities involved in the effective engagement of the target by a weapon. Instead it uses a single probability, probability of fire (P_F), to determine the outcome of an engagement. While this simplistic approach may have been effective for an explode-in-place architecture, it leaves significant gaps in the ability to understand and compare the performance of various weapons, including mixes of weapons, and targeting logics in an advanced

FUWS. MFSA must be capable of modeling multiple weapon types and configurations of mixed weapons types with a number of targeting logics.

3. Scenario Limitations

GAMET employs a simple, one-at-a-time transit of target vessels in the simulation. While this may be adequate for legacy minefields, it does not provide users with an understanding of the complicating impacts on targeting logic associated with the presence of multiple target vessels. Simply put, when evaluating a mobile weapon such as a torpedo it is important to consider other vessels in the same vicinity. MFSA must be capable of modeling scenarios in which multiple target vessels are simultaneously transiting the minefield.

4. Usability Limitations

Finally, the current version of GAMET is a complex software tool suitable for use by trained analysts, but not necessarily by operational planners. In fact, the "GAMET User's Guide" directs users to partner or consult with GAMET developers when building a scenario. The GAMET architecture requires users to provide formatted parameter data in at least nine different input files. The data input formats are so cumbersome, the User's Guide recommends copying and editing sample sets of data to minimize input errors (Belton 2015, 1–3). As a result, users trained in a NPS project criticized the cumbersome user interface (Bard 2013, 22). MFSA must be capable of broad acceptance by the operational planning and program analyst user communities by providing a flexible and intuitive user interface.

III. REQUIREMENT IDENTIFICATION

> In our approach, "requirements" and "interface definitions" are treated in the same way using common semantics. This is because the two are intimately linked and quite often viewed as the same because they both represent binding contracts. Requirements are a contract between a developer and those stakeholders that interact with the developer. Interfaces enable communication and interaction between elements within a system as well as between the system and its environment. In the interest of simplification, we employ the term "requirements" from this point on as short for both *requirements* and *interface definitions*. (Madni and Sievers 2014, 43)

This chapter presents the Mental Focus team's approach to requirement discovery by identifying the MFSA functional interfaces and articulating the information exchanges at these interfaces. Using a discovery process of UML use case identification and elaboration (Pressman 2015, 173), the team further decomposed these requirements. This process of information exchanges informed the development of the system architecture requirements described in future sections.

A. USER CLASSES

The team began by analyzing the active stakeholders (Chapter II, Table 4) and their associated information needs. The team identified four classes of users that would interact with the system and require system interfaces. Shown in Figure 14, these user classes are grouped into two principal categories: customers of MFSA outputs and providers of MFSA inputs. These different perspectives on the MFSA and the users' interactions with it assisted the team in the development of a flexible architecture that addressed multiple stakeholder needs.

1. Program Analyst

The Program Analyst user class includes both the acquisition professional, concerned with cost, schedule, and performance tradeoffs of various available technologies, and the system development engineer, concerned with how different component characteristics affect overall system performance. For example, an analyst

may want to quickly perform a parametric study to see which variables produce the optimal results or the analyst may want to run a series of more detailed scenarios to supplement and mitigate the expense of live-fire testing. The program analyst will likely be satisfied to use generic, or representative approximations of operational environments with detailed descriptions of the weapon system and threat. Ultimately the analyst is interested in "what is possible in the future" with a FUWS and "what is the optimal allocation of resources" to support the procurement of a future FUWS system acquisition or upgrade. The team envisions that this class of user encompasses users from NAVSEA, including the component program offices and warfare development centers.

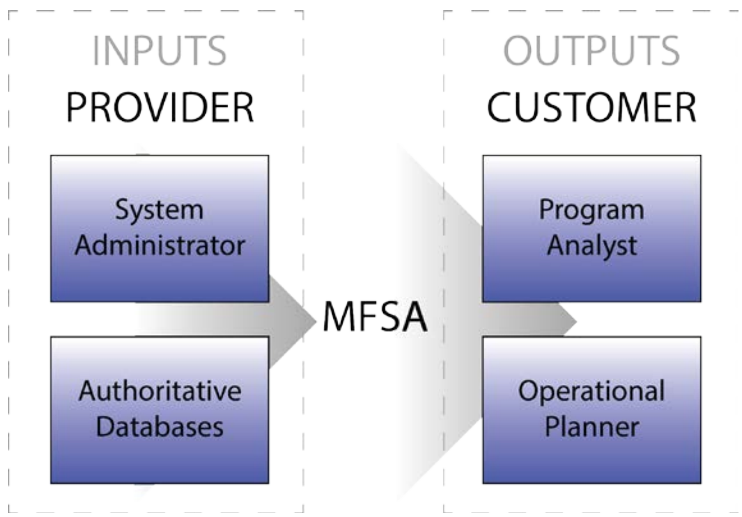


Figure 14. User Class Diagram

2. Operational Planner

The second intended user class consists of Operational Planners, and represents the warfighter applicability of MFSA. These users are planning and providing military capabilities to operational commanders, within defined mission constraints. They are interested is ensuring that assigned resources and available FUWS components are arranged to provide the required capability. These users will likely desire to use the best environmental data available to predict performance in a specific tactical scenario. While the operational planner may coordinate with developers in the refinement of future

FUWS requirements, the operational planner is principally concerned with "what is possible with FUWS assets currently available."

The design approach proposed by the Mental Focus team assumes the operational planner has an informed technical background and is familiar with both the employment of undersea weapon systems and the dynamics of the undersea environment. The team envisions that this class of user encompasses users from operational commands, such as Joint Force Maritime Component Commanders, and reach-back planning support commands such as the Naval Surface and Mine Warfighting Development Center (SMWDC).

3. System Administrator

The team added a third user class, the system administrators, whose role is providing and maintaining the required input information. While in practice a system developer or operational planner may also be a system administrator, the team determined that establishing a separate role for the responsibility of maintaining input data libraries would simplify the behavioral modeling of MFSA interactions with users. It would also assist the team in subsequent analysis and discovery of sustainment and maintenance requirements.

The system administrator role would also include system maintainers and the in-service engineering agent (ISEA), who maintains configuration control and validation authority over the data being supplied to the MFSA system.

4. Authoritative Databases

Finally, the Mental Focus team recognized the need for MFSA to pull data from authoritative databases of information, either via the system developer or via direct interface. Databases of environmental, threat, weapon and sensor data exist and are maintained by numerous offices in numerous formats. It would be impractical for MFSA to compile and maintain a single central database from all these various sources, thus individual MFSA installations would need to be capable of tracing the pedigree of data input streams in order to support user confidence in simulation outputs. In an ideal

architecture, MFSA would be capable of interfacing directly with authoritative databases to ensure the most current and accurate information is used in the simulation.

B. MFSA INPUTS AND OUTPUTS

The Mental Focus team next analyzed the customer stakeholder concerns (Chapter II, Table 4) and associated information needs to establish high-level groupings of system output and input requirements. As seen in Figure 15, and further articulated in Table 6, the team identified two top-level groupings of functional outputs and four groupings of inputs.

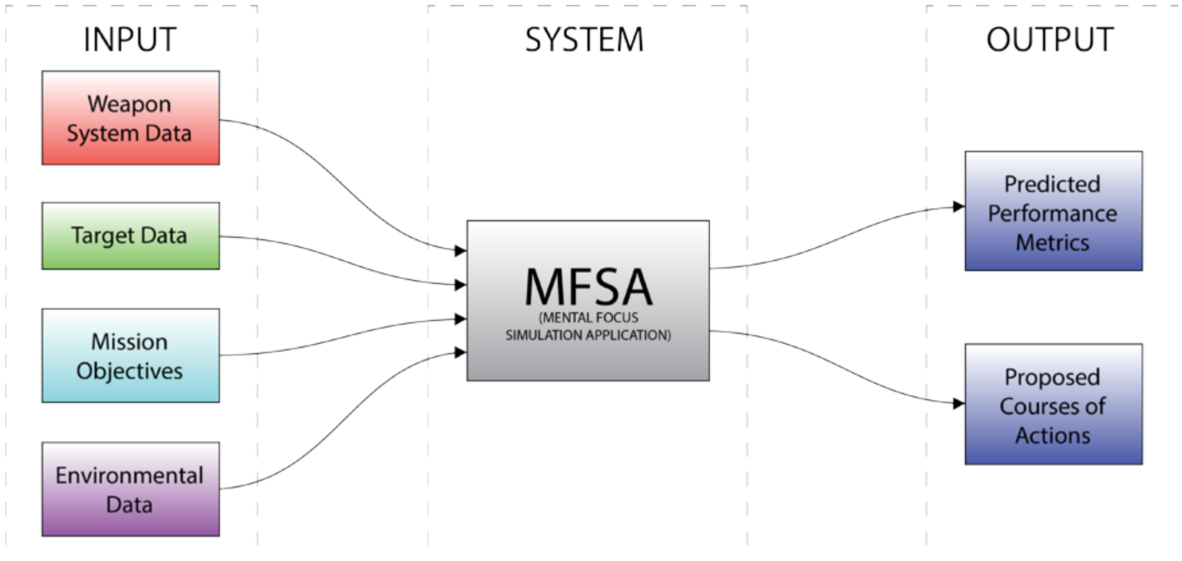


Figure 15. MFSA Functional Inputs and Outputs

Next, the team translated these concerns and needs into the high level MFSA output requirements provided in Table 6 (Req.2.1 and Req.2.2). Starting from these high-level functional output requirements, the team derived categories of data inputs required to calculate the required outputs. In addition to data about the FUWS, the team identified a need for information about the target, the environment, and the goals of the operational commander as MFSA inputs. These categories of data are summarized in the high level MFSA input requirements in Table 6 (Req.1.1 thru Req.1.4).

Table 6. MFSA Functional Input-Output Requirements

Requirement	Threshold	Objective
Req.1.1 MFSA *shall simulate* future weapon systems *by using data* representing the performance of undersea sensors, kinetic and non-kinetic effectors, associated communicators and fire control and targeting logic	Simulates existing technologies	Simulates technologies at or above TRL 5
Req.1.2 MFSA *shall simulate* exchange of EMI in the undersea environment *by using data* describing the environmental conditions of the area of concern	User input environment data	External database input
Req.1.3 MFSA *shall simulate* targets operating in the area of concern *by using data* on target physical parameters, signal sources and operating characteristics	Simulates surfaced military vessels	Simulates surfaced or submerged military vessels and neutral vessels
Req.1.4 MFSA *shall simulate* various mission objectives defined by the operational commander	Selected friendly and enemy mission sets	User designed friendly and enemy missions
Req.2.1 MFSA *shall calculate and predict* measures of effectiveness and performance obtained in a scenario	Current doctrinal MIW measures of effectiveness and performance	Customizable measures of effectiveness and performance
Req.2.2 MFSA *shall calculate and propose* the number, type and placement of sensors, effectors and/or command and control (C2) nodes required to achieve either a desired effectiveness or the optimal effectiveness within a resource limit	Optimal configuration proposed	Efficient frontier of cost effectiveness proposed

In each case the proposed threshold and objective levels of performance describe the team's analysis of the stakeholder's needs and wants. Understanding the MFSA output capabilities are a function of the inputs captured, the team focused its energy on decomposing the input requirements in Table 6 using use cases and scenario narratives.

C. COMMON USE CASES

The identified input and output requirements were validated using Unified Modeling Language (UML) use case. Figure 16 shows the primary actors interfacing with the system and the use cases (Pressman 2015, 875) that describe the intended use of the proposed MFSA system, guide the development of requirements models, and support requirement discovery.

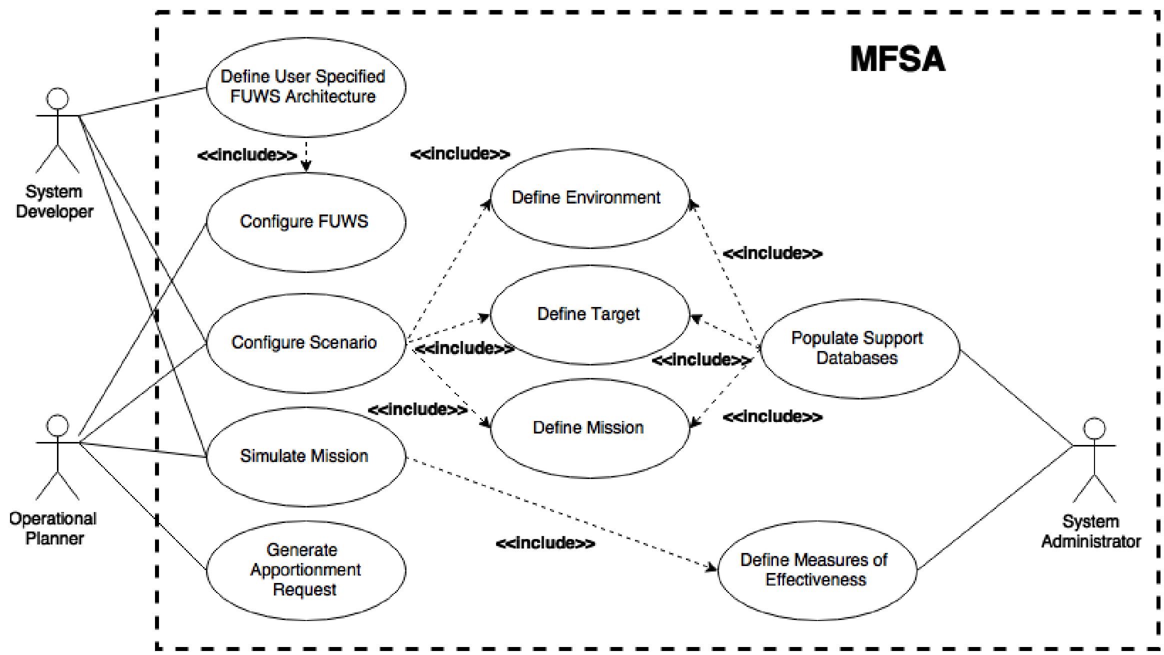


Figure 16. MFSA Use Cases

Note the parallel paths and overlaps shown in Figure 16 between the FUWS program analyst and operational planner user experiences. While both of these classes of users are concerned with using MFSA to obtain decision support information, they have slightly different information needs. The analyst desires to understand the trade space between various FUWS technical parameters; the operational planner requires the ability

to assemble and predict the performance of a specific configuration of FUWS components to provide a military capability.

1. Use Case: Configure Scenario

In this use case, the user logs into MFSA with the tools and options configured for the anticipated set of tasks performed by that user. After logging in, the user first *configures a scenario.* To do this, the user may either create a new scenario or to select a previously scenario from a database and continue analysis. When selecting a new scenario, the user defines the *environment* in which the FUWS will operate (Req.1.2), the *target* the FUWS will counter (Req.1.3), and the operational commander's *mission* or objective (Req.1.4).

To define the environment, the user is presented with a choice: create a user-defined environment, import environmental data from an external database or library, or load an existing environment from a database of previously saved work. When developing a user-defined scenario, MFSA will provide the user with an indication of the model maturity level as well as identify the minimum required input parameters. The team anticipates the minimum environmental requirements include geographic boundaries and water depth data. Table 7 provides a decomposition of Req.1.2 into a list of potential environmental parameters that may be utilized by MFSA to provide higher levels of simulation resolution. Appendix C provides additional details on the functional purpose of these parameters within the MFSA simulation process.

As seen in Table 7, the team envisioned three levels of simulation resolution (basic, intermediate, and advanced), each requiring additional levels of input data and providing more detailed analysis. These resolutions provide a relative scale of MFSA analysis detail available based on the available input data and can assist the user in determining the input requirements required to achieve higher levels of model fidelity.

Table 7. MFSA Environmental Input Parameters (Req.1.2)

Environmental Parameter	Basic	Inter	Advance
Geographic boundaries	X	X	X
Water depth	X		
Bathymetric profile		X	X
Sound velocity profile (SVP)			X
Current		X	X
Ambient noise level (AN)		X	X
Ambient noise frequency range			X
Seismic background noise			X
Bottom type / Bottom loss		X	X
Fixed obstacles (e.g., oil rig)		X	X
Probabilistic obstacles			X

Following the definition of the environmental parameters, the user is prompted to define the target. As before, the user is presented with a choice: create a user-defined target, import target data from an external database or library, or load an existing target from a database of previously saved work. Again, MFSA will provide the user with an indication of the model maturity level and the minimum required input parameters. The team anticipates the minimum target data requirements include target course and speed, target acoustic and magnetic signatures, target mission, and target sequence number. Table 8 provides a decomposition of Req.1.3 into a list of potential target parameters that may be utilized by MFSA to provide higher levels of simulation resolution.

The final step in setting up a scenario is defining the operational commander's intended *mission*, including objectives, restraints and constraints. As before, the user is presented with options: create a user-defined mission or load an existing mission from a database of previously saved work. Table 9 provides a decomposition of Req.1.4 into a list of potential mission parameters that may be utilized by MFSA at various levels of simulation complexity.

Table 8. MFSA Target Input Parameters (Req.1.3)

Target Vessel Parameter	Basic	Inter	Advance
Number (1 to n)	X	X	X
Course	X	X	X
Speed	X	X	X
Max speed		X	X
Class/type		X	X
Target mission	X	X	X
Displacement		X	X
Length		X	X
Width (Beam)		X	X
Draft		X	X
Damage susceptibility	X	X	X
Magnetic signature	X		X
Acoustic signature	X		X
Ship countermeasures			X
Maneuvering tactics		X	X
Countermeasures tactics			X
Mine hunting mission			X
Mine sweeping mission			X
Hull material		X	X
Target priority		X	X

Table 9. MFSA Mission Input Parameters (Req.1.4)

Mission Parameter	Basic	Inter	Advance
Limited Rules of Engagement			X
Human "in loop" required			X
Target discrimination required		X	X

2. Use Case: Configure FUWS

In this use case, the user has previously logged on and configured a scenario. The user then *configures the FUWS*. The user may either load existing configuration or create a new configuration. When selecting a new scenario, the user defines the *environment* in which the FUWS will operate, the *target* it will counter, and the operational commander's *mission* or objective (Table 10).

After the user has constructed the scenario then next step is the construction of the minefield, either by manually placing the assets into the environment, or by using an

automation function which will apply "rules of thumb" to generate a configuration to meet the intended performance objectives. The user will build the FUWS architecture based on sensors, communication technologies, weapons and command logic from a database within MFSA. One of the features unique to the analyst role is the ability to *define new components* and/or modify existing components and add those to the MFSA database. This will allow the developer to perform system analysis to inform technology investments and priorities.

Table 10. MFSA FUWS Input Parameters (Req.1.1)

FUWS Parameters	Basic	Inter	Advance
Sensors			
Number (1 to n)	X	X	X
Sensor Type	X	X	X
Position	X	X	X
Probability Detect v Range	X	X	X
Bearing Accuracy		X	X
Reliability		X	X
Timing			X
Endurance / Power Usage			X
Communicators			
Range	X	X	X
Data rate		X	X
Latency		X	X
Reliability		X	X
Endurance / Power Usage			X
Weapons			
Number (1 to n)	X	X	X
Weapon Type	X	X	X
Position	X	X	X
UUV Weapon Batteries	X	X	X
Intercept Speed	X	X	X
Search Speed	X	X	X
Explosive power	X	X	X
Range	X	X	X
Endurance		X	X
Reliability		X	X
Weapon Search Pattern			X
Targeting Logic	X	X	X

3. Use Case: Simulate Mission

Upon successfully populating the model a “run simulation” button will become available. The user will have the option to run a single simulation or run a series of simulations for Monte Carlo analysis. An option to run the simulation graphically will be available to help the developer visualize how the system is performing in real time. This feature will help with tailoring the configuration or troubleshooting a simulation that does not produce the desired results. After the simulation completes the selected number of runs, a summary of the data will be provided on the screen, along with the selected measures of performance of Table 11.

Table 11. MFSA Predicted FUWS Performance Outputs (Req.2.1)

MOP/MOE Outputs	Basic	Inter	Advance
Simple initial threat (SIT)	X	X	X
Threat profile (1 to n)	X	X	X
Expected time to engagement		X	X
Expected casualties	X	X	X
Resistance to channeling	X	X	X
Probability of detection (P_d)	X	X	X
Probability of classification (P_c)		X	X
Probability of engagement (P_F)			X
Probability of kill (P_k)		X	X
System failures		X	X
Fratricide risk			X
Expected false engagements			X
Expected unused ordinance			X

4. Use Case: Generate Apportionment Request

This use case assumes the completion of the “configure scenario” use case and is provided as an alternative to the “configure FUWS” use case. It allows the user to identify required operational counter-mobility effects as FUWS measures of performance and resource constraints. When sufficient data is available, MFSA will allow the user to “generate system requirements” and will provide the user with an asset configuration (or configurations) that provides the desired level of performance as seen in Table 12. This planning function provides the predictive optimization feature of MFSA and generates the outputs required to address Req.2.2 of Table 6.

Table 12. MFSA Proposed Configuration Outputs (Req.2.2)

FUWS Configuration	Basic	Inter	Advance
Optimal configuration of single asset classes proposed	X	X	X
Optimal configuration of mixed asset classes proposed		X	X
Efficient frontier of cost effectiveness			X

IV. NON-FUNCTIONAL REQUIREMENTS

Non-functional requirements provide a description of a system's required characteristics that are not directly traceable to the system's raison d'etre. While necessary to the accomplishment of the system's mission, they are a consequence of the system's existence. As reflected in the terminology of Stellman and Green who refer to them with such terms as "constraints," "quality attributes," and "non-behavioral requirements" (2005, 113); non-functional requirements are often qualitative. However, as seen in Figure 17, these qualitative concepts can often be mapped to proxy, quantitative metrics.

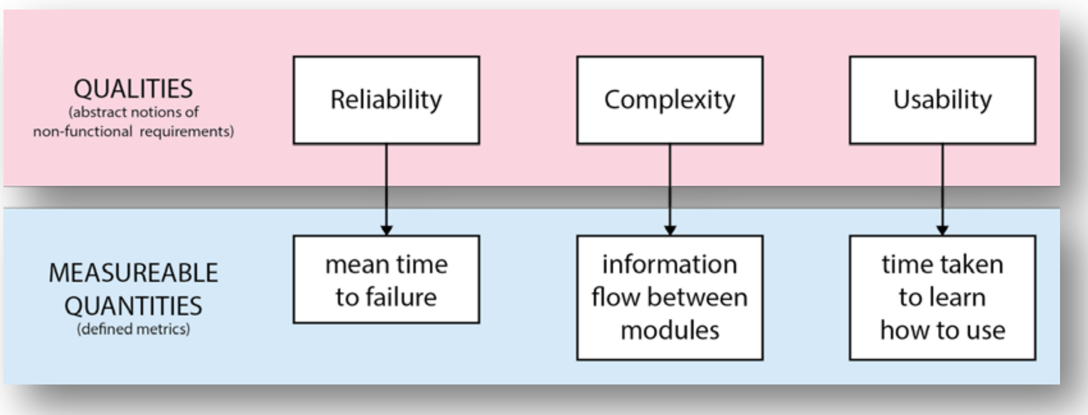


Figure 17. Non-Functional Requirements to Metrics (source: Budgen 1994)

This chapter describes the non-functional requirements most relevant to MFSA development and describes a process by which these traits should be implemented. The team identified key considerations and best practices, which will lead to a quality MFSA product and to high end-user satisfaction. The non-functional requirements were grouped in two broad categories:

- operational requirements which focus on the user experience
- maintainability and supportability which focus on life cycle logistic support

A. OPERATIONAL REQUIREMENTS

1. Usability

> If a product is to be successful, it must exhibit good *usability* — a qualitative measure of the ease and efficiency with which a human can employ the functions and features offered (Pressman 2015, 317)

Usability, by definition, is subjective based on the user's experience interacting with the software and thus requires user interaction early in the system life cycle to design and evaluate. This can be done using iterative approaches such as the spiral development model shown in Figure 18 (Pressman 2015, 323). To support this iterative approach, the team developed a prototype simulation tool, described in Chapter VI, that provided an interface for user validation. Additionally, based on feedback from users[10] and the design principles discussed in this section, the team developed a second interface mockup, discussed in Appendix I, which provides a vision of a fully operational MFSA graphical user interface.

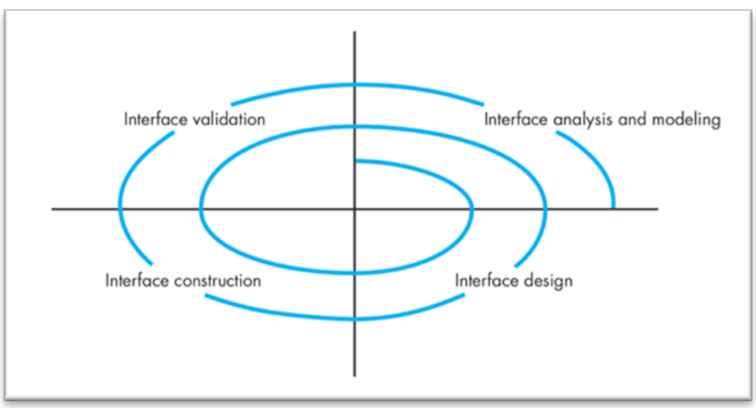


Figure 18. Spiral Process for Interface Design (source: Pressman 2015, 324)

Tognozzi provides a set of design principles (via Pressman 2015, 338–339), which can support development of software system usability. The team considered these

[10] Team members role-played as stakeholder users when interacting with the prototype to accelerate the user feedback timeline within project constraints.

principles and selected the following six principles for articulating MFSA usability requirements.

1. Flexibility.

MFSA shall support flexible user input modes. As described in Chapter III, MFSA requires numerous user inputs (Req 1) to configure the FUWS components, construct the simulation environment, and run the simulation. In order to make the process less time consuming and more user-friendly, MFSA should support multiple input modes wherever practical to increase flexibility. As an example, the user may select the number of weapons in a given minefield by either dragging a slide bar to a desired number or by typing in the number. Having the ability to select from multiple input modes allows a user to choose a comfortable method.

2. Metaphors.

MFSA shall use a visual layout based on naval tactical systems. This technique provides the user with familiar visual cues to help guide the interactive process and understand the components in the simulation. When constructing the environmental conditions and boundaries of a minefield, MFSA will display a graphical representation of the area with bathymetry visualized using color gradients. FUWS system components should be represented with icons consistent with Common Warfighting Symbology (MIL-STD-2525B) whenever possible. The expected user community will be familiar with and comfortable with these metaphors (McFadden et al. 2008, iii), which will help enable widespread adoption.

3. Consistency.

MFSA shall provide a user interface consistent with the Global Command and Control System, Maritime (GCCS-M) interface. Unless there is a compelling reason for change, using patterns which are familiar to the user enhances the user experience. Using the GCCS-M interface pattern will provide a user experience likely to be familiar to operational users of the system and decision makers. This will also support integration with other warfare area planning tools.

4. Human Interface Objects.

MFSA shall use existing object libraries to provide user interface objects. Implementing familiar design patterns, such as drop down menus, and sliders, will help make MFSA more intuitive to use, reduce learning time, and improve efficiency.

5. Controlled Autonomy

MFSA shall guide the user through the simulation setup and execution. The user must be presented with an intuitive path to constructing a functional model based on the inputs the user has already provided. Additionally, since the accuracy and validity of the results produced by MFSA relies heavily on user inputs, it is essential MFSA to provide immediate feedback on problems with data inputs. Where practical, it would be helpful to provide real-time error checking, such as: checking for typos (character in place of a number), logical inconsistencies (negative water depth), unit checking and conversion (feet to meters).

6. Track State

MFSA shall support tracking completed and remaining user actions. The user time investment in developing a scenario may be extensive. MFSA must be capable of allowing the user to save and return at a later time to continue development. Also, in support of the controlled autonomy principle above, MFSA should provide a method for tracking status to show which tasks have been completed and which remain. This feature serves two purposes; first, it informs users how far along they have progressed in the work flow, and it also allows users to return to where they left off should they decide to logout for a period of time.

2. Reliability

The project team evaluated the two components of reliability of greatest concern to key stakeholders and user groups: the software reliability and the database network reliability.

1. Software Reliability

MFSA shall reliably operate reliably, conforming to user expectations for reliability. Software failures can be minimized by proper detailed design and testing. MFSA development should conform to MFSA should conform to the guidelines of IEEE P1633, *Recommended Practice on Software Reliability*. During MFSA development, appropriate reliability studies should be conducted to provide a suitable estimate of the quality of the final product. This involves modeling performance, measuring key factors for reliability, and implementing improvements where possible.

2. Database Network Reliability

MFSA shall be capable of operating in the Joint Information Environment, exchanging data with a network of authoritative databases as well as capable of operating on shipboard local area networks. In Chapter III, the team identified the need for MFSA to pull data from authoritative databases of information via direct interface. Because MFSA may be deployed to shipboard networks, isolated from these authoritative databases, MFSA must be capable of operating without direct interface to these databases.

3. Net Ready KPP

MFSA shall be Net Ready compliant in accordance with CJCSI 6212.01F. The Net-Ready Key Performance Parameter (NR KPP) is a required component of all Joint Capabilities Integration and Development System (JCIDS) information system (IS) requirement documents. Table 13 provides a summary framework that can be used to further develop MFSA technical requirements and satisfy the three NR KPP attributes.

Table 13. NR KPP Summary Framework (adapted from JCIDS-M 2015, D-E-5)

NR KPP Attribute	Attribute Details	Measures
Support to military operations	Counter-Mobility/ Naval Mine Warfare	Hours delay in enemy force movements caused by mines/ obstacles. % of enemy forces unable to reach their objective due to mines/ obstacles.
	NTA 1.4.1.1 Plan Minefields NTA 5.4.3.6 Coordinate Offensive Mining Operations	Hours to coordinate minefield plan and input to mine tasking order. Planned minefield effectiveness achieved at > 50% SIT.
Enter and Managed on network	Joint Information Environment Shipboard Tactical Network	MOP for entering network
		MOP for management in network
Effectively Exchanges information	Consumes data on environment, threats, and systems. Produces information on minefield plan and performance	MOP for information exchange

4. Cyber Security and Information Assurance

MFSA shall conform to information security requirements of DoDI 8500.01E "Cybersecurity" and DoDI 8510.01 "Risk Management Framework for DOD Information Technology." Four policy requirements of particular importance to MFSA are summarized below.

1. Risk Management

Cybersecurity threats shall be managed by a multi-tiered risk management approach. This process ensures risks and vulnerabilities of a system are properly identified, tracked, and mitigated in order to protect DOD information and assets.

2. Operational Resilience

Information and services are available to authorized users when required. This involves implementing a security posture that, whenever possible, provides the ability to reconfigure, optimize, self-defend, and recover with little or no human intervention.

3. Integration and Interoperability

Requires that each IS achieve interoperability by adherence to DOD standards and instructions, ensuring that vulnerabilities are not introduced to a network through a weak node or system.

4. Identity Assurance

Provides assurance that only authorized users can gain access to systems and eliminates anonymity on networks by implementing Public Key Infrastructure (PKI) as a means to manage user identity.

B. MAINTAINABILITY AND SUPPORTABILITY REQUIREMENTS

> Software maintenance is the modification of a software product after delivery to correct faults, to improve performance or other attributes. (ISO/IEC 14764:2006)

MFSA shall receive updates and patches to add functionality, support hardware and operating system upgrades, and correct user identified errors. While maintenance is generally associated with fixing defects, the MFSA conceptual design also involves administrative maintenance, described in Chapter III, to maintain the currency and accuracy of information used to describe assets and threats in the simulation architecture. Thomas Pigoski suggests that roughly 80% of software maintenance efforts are non-corrective actions. This rather extensive effort involves adding features to improve functionality and user experience. As described previously, the architecture of the software relies on local administrators to update and maintain technical accuracy for specifications of simulated assets. These administers will also implement updates and patches.

MFSA shall include an interactive electronic technical manual (IETM). This manual represents the minimum level of supportability required and will provide the user with tutorials, explanations of features, and instructions for use. In addition to the static

help file, the team anticipates an online community of practice utilizing a secure service, such as Intellipedia,[11] to share FUWS architectural designs and lessons learned.

[11] Intellipedia provides a secure, online environment for collaborative data sharing by the Intelligence Community and Department of Defense.

V. PROPOSED ARCHITECTURE

> The two architectures [functional and physical] are developed in parallel but with close interaction to ensure that the allocated architecture is meaningful when the functional and physical architectures are combined. (Buede 2009, 27)

This chapter proposes a MFSA architecture, including functional and physical (or structural) expressions and the allocation of identified requirements to the architecture. While the architectures are discussed in separate sections for clarity and organization, development of the architectures in the Innoslate[12] MBSE tool ensured the architectures were appropriately traceable.

A. FUNCTIONAL ARCHITECTURE

> [A function is] an activity or task that the system performs to transform some inputs into outputs (Buede 2009, 211)

> An *Action* … specifies the mechanism by which inputs are transformed into outputs. (LML 2013, 11)

Using a top-down approach, the team began by decomposing the context action, *Action.0.0 Perform MFSA Actions*, into the top-level actions shown in Figure 19. The team proceeded to use SysML sequence diagrams to communicate system interactions and LML action diagrams to communicate the required system behavior.

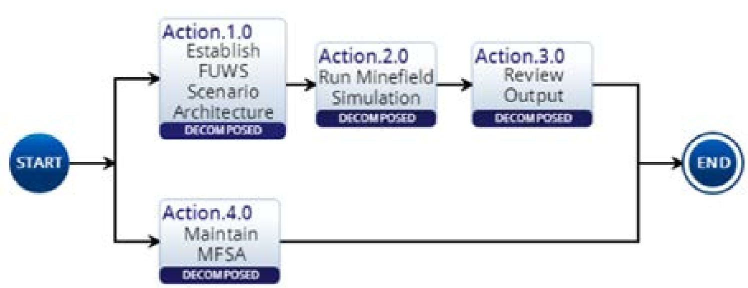


Figure 19. Perform MFSA Action Diagram

12 Innoslate is a collaborative web based tool, developed by SPEC Innovations, that supports development of model based artifacts and execution of model verification simulations. Innoslate supports a number of architectural artifacts in both Life cycle Modeling Language (LML) and Systems Modeling Language (SysML).

The first sequence of actions, shown in the top parallel of Figure 19, is representative of the actions taken by the user to define a scenario, simulate the scenario and review the results of the scenario. In parallel with these actions, the system administrator maintains the system. This includes pre-populating the system with the required information to support simulation of new FUWS technologies, alleviating the legacy burden on the end-user of validating and formatting data inputs.

1. Establish FUWS Scenario

Decomposing the first action, *Action.1.0 Establish FUWS Scenario Architecture*, the team developed a sequence diagram, Figure 20, to show the interactions required in the development of a FUWS Scenario. This diagram shows the user logging into MFSA, selecting the desired scenario type, and selecting the desired FUWS architectural components. Included in the selection of scenario type are options to open previous scenarios, template scenarios, and new blank scenarios. Once the selected scenario space has opened, the user selects the FUWS architectural components.

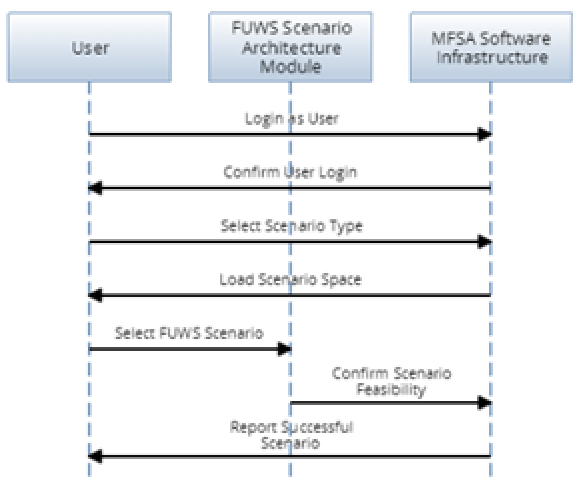


Figure 20. Sequence Diagram of Action 1.0 Establish FUWS Scenario

This sequence diagram can be viewed as a LML Action Diagram, as seen in Figure 21. In addition to the sub-actions shown sequence diagram, the action diagram shows the inputs (or triggers) and outputs from each action.

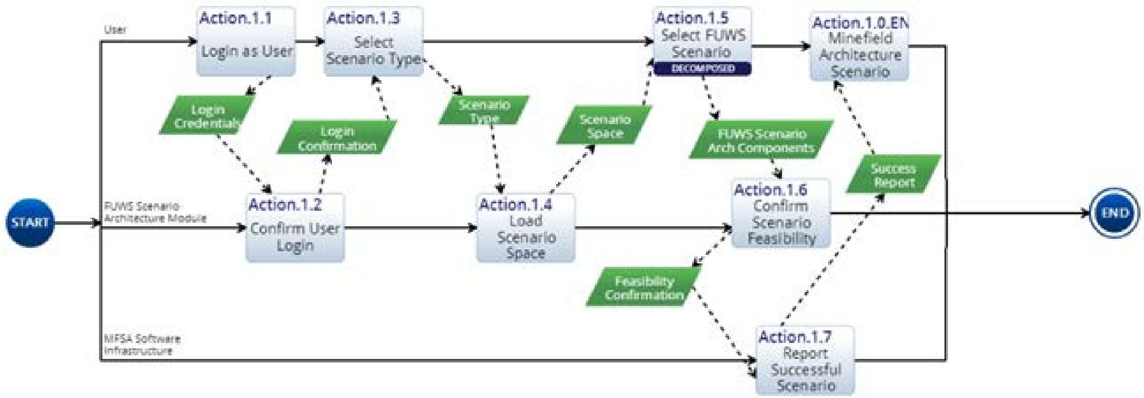


Figure 21. Action Diagram of Action.1.0 Establish FUWS Scenario

The team continued with decomposing *Action.1.5 Select FUWS Scenario* to highlight the functionality of the MFSA system. The sequence diagram of Figure 22 shows specific interactions between the user and MFSA required in defining the minefield environment, in specifying the FUWS assets (sensors, communicators and weapons) that comprise the minefield, and in integrating those assets in a selected configuration. The user may also select the anticipated target scenario and desired MOPs. Throughout the selection process, MFSA confirms that selections are both valid and congruent. If selection conflicts with previous selection, MFSA will inform the user of the conflict.

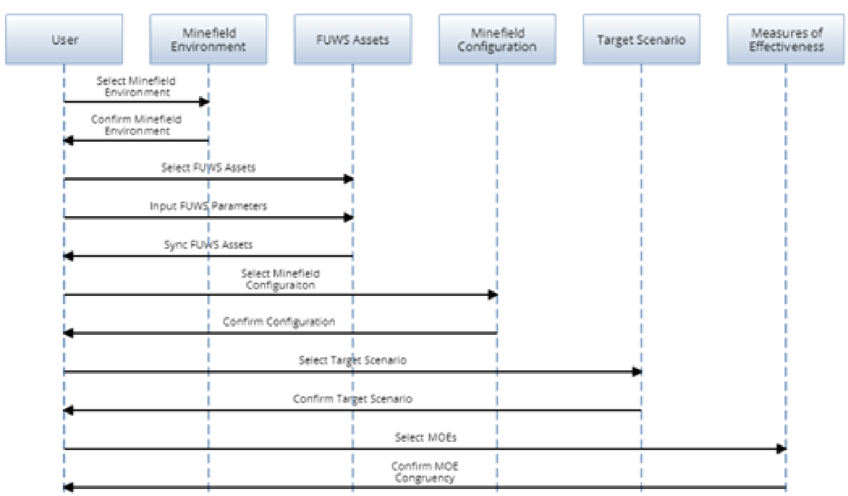


Figure 22. Sequence Diagram of Action.1.5 Select FUWS Scenario

By displaying *Action.1.5 Select FUWS Assets* as a SysML Action Diagram, the team was able to incorporate an OR construct to differentiate between the use of MFSA as an operational planning tool and a capability development tool. As shown in Figure 23, the user can either select *Action.1.5.4 Select FUWS Assets* to evaluate or maximize the performance of a given set of capabilities or select *Action 1.5.5 Input FUWS Parameters* to input desired performance parameters, using MFSA to generate a set of required components.

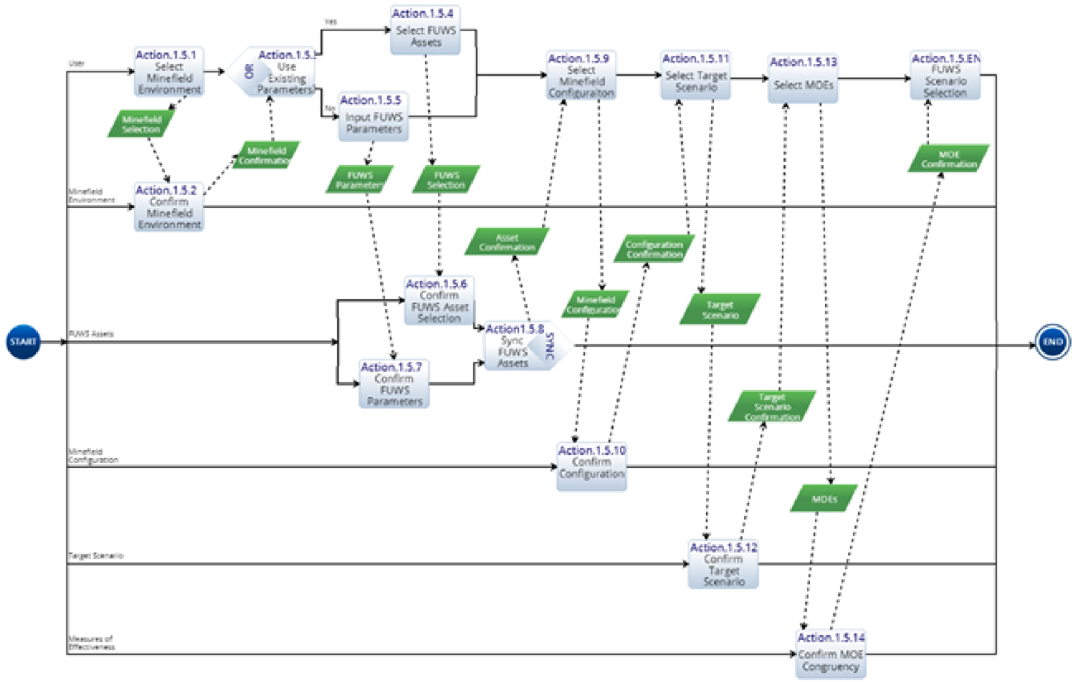


Figure 23. Action Diagram of Action.1.5 Select FUWS Scenario

2. Run Minefield Simulation

After the system collects the required inputs to establish the scenario, MFSA utilizes Monte Carlo simulations in *Action.2.0 Run Minefield Simulation* to translate these inputs into the desired outputs. This action, shown in Figures 24 and 25, begins when the user initiates the simulation. As seen in the sequence diagram the simulation uses the information previously selected by the user to generate data sets and calculate the required MOEs.

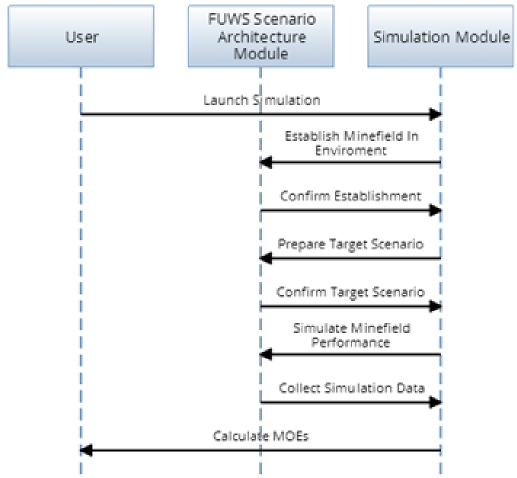


Figure 24. Sequence Diagram of Action.2.0 Run Minefield Simulation

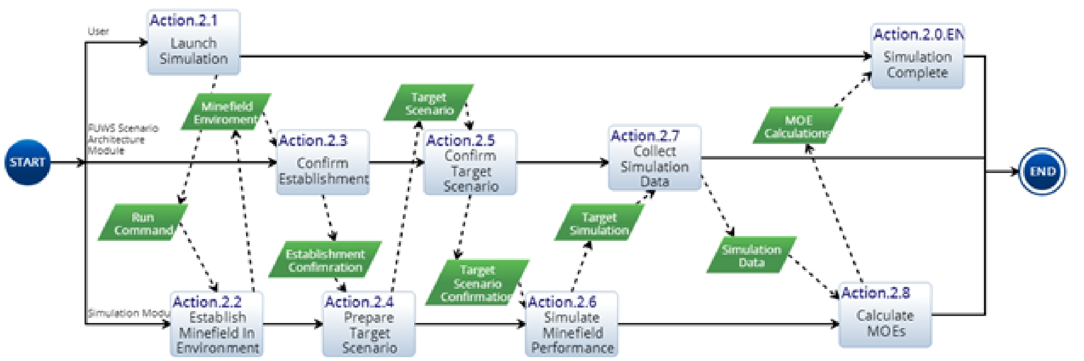


Figure 25. Action Diagram of Action.2.0 Run Minefield Simulation

3. Review Output

The final step in the MFSA user sequence is the *Action.3.0 Review Output* Action, decomposed in Figures 26 and 27. In this action, MFSA generates a formatted output report that is significant and meaningful for the user. The action is initiated by the user requesting the output report or automatically upon completion of the run simulation action. The output report module requests data from the simulation module and formats the data into a clear and concise report for the user. Not shown in these figures is the potential for the user to decide to re-perform the analysis with a modified set of inputs. This would represent a system-wide loop, as the user would return to Action.1.0 to make

the desired revisions. This looped process would continue until the user gathers all required data and results.

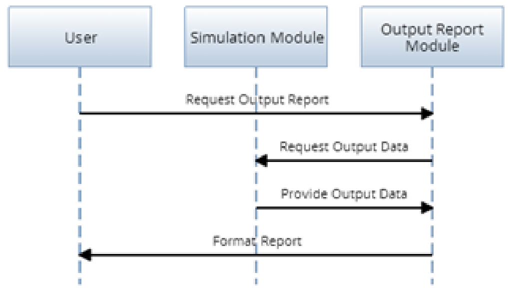


Figure 26. Sequence Diagram of Action.3.0 Review Output

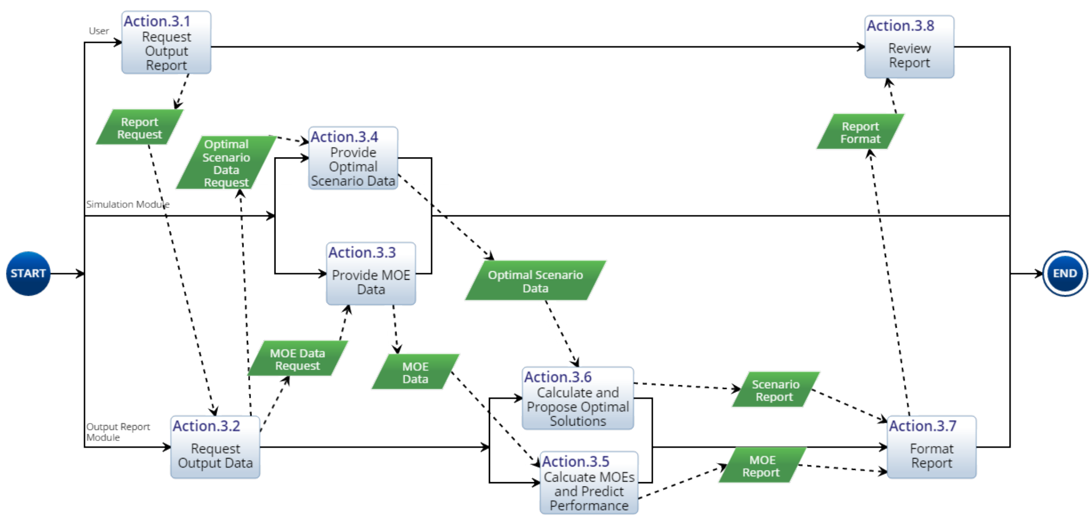


Figure 27. Action Diagram of Action.3.0 Review Output

4. Maintain MFSA

As seen previously in Figure 19, in parallel with these tasks, MFSA must be maintained. This could include the system administrator updating the different MFSA modules to remove software bugs, providing future system usability enhancements, and updating databases to reflect changes in FUWS technologies, targets or environments.

As shown in Figures 28 and 29, in *Action.4.0 Maintain MFSA* the system administrator logs into MFSA with a different login protocol from the user. This provides the system administrator with greater permissions to access and alter system components.

As the system administrator makes updates to the different modules, MFSA provides prompts to confirm the updates prior to allowing the administrator to promulgate updates to other users.

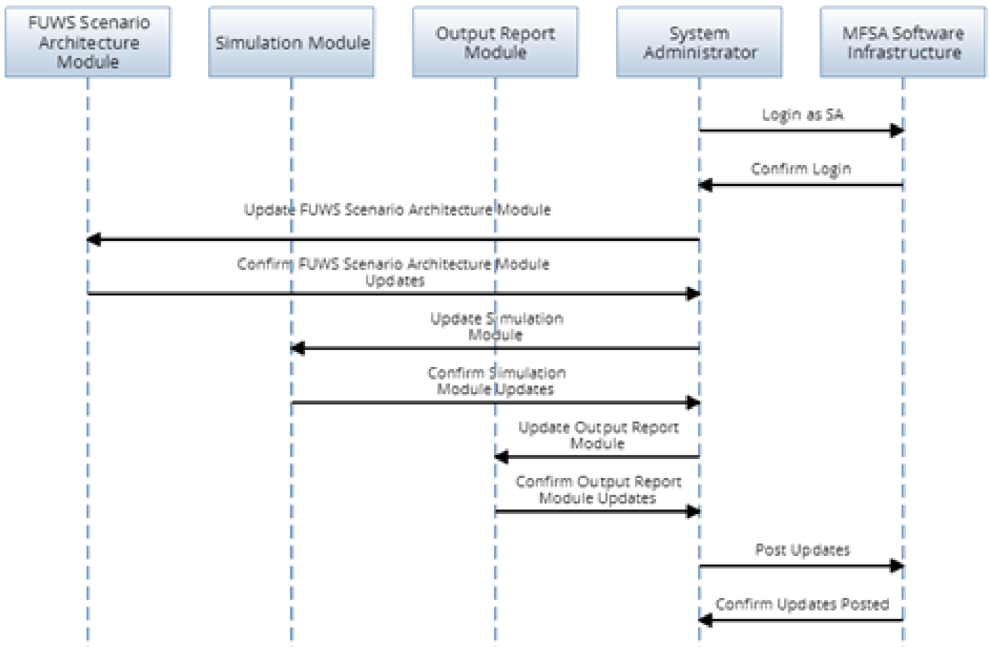


Figure 28. Sequence Diagram of Action.4.0 Maintain MFSA

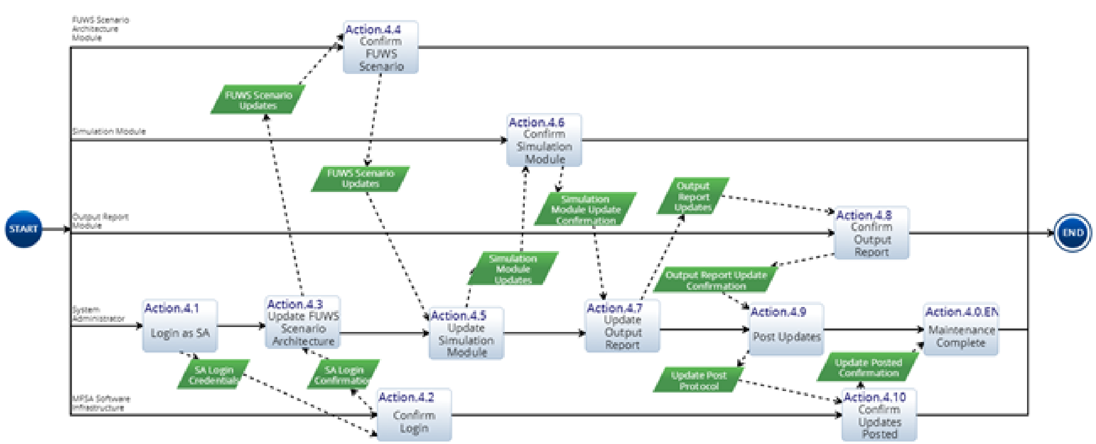


Figure 29. Action Diagram of Action.4.0 Maintain MFSA

B. STRUCTURAL ARCHITECTURE

> The physical architecture provides resources for every function identified in the functional architecture. (Buede 2009, 253)

Because the MFSA system is an information system, many of the assets[13] in the "physical" architecture are software components that perform allocated functions. As such, the team utilized the term "structural" to include traditional "physical" system architecture components as well as non-tangible, software module assets.

1. Structural Hierarchy

As seen in Figure 30, the MFSA asset can be decomposed into component software modules, the supporting MFSA software infrastructure, and the system administrator. The team chose to include the system administrator inside the system boundary because this role would be "created" as part of the system development. The program analysts and operational planners that compose the "user" asset are shown external to the system and there interactions with the system are shown in subsequent views of the structural architecture. *Asset.2.0 FUWS Scenario Architecture Module* was further decomposed to highlight the components of the FUWS and support traceability of the previously identified (Table 6 in Chapter III) input requirements.

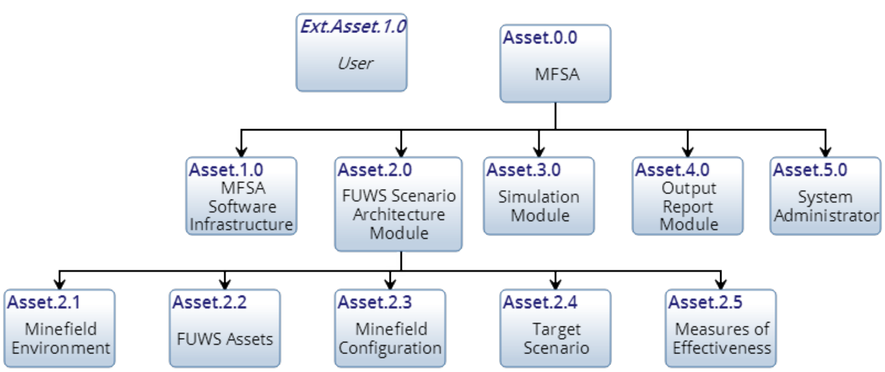


Figure 30. Structural Hierarchy Diagram of MFSA

[13] An *Asset* is an object (system, subsystem, component, or element), person, or organization that performs *Actions* (LML 2013, 11)

2. Class Diagram

While useful for tracing the assignment of assets to functions in the architectural model, the hierarchy diagram provides limited information about the assets and their relationships. A Unified Modeling Language (UML) Class Diagram provides an appropriate mechanism for showing the required relationships between the assets and supports translating the conceptual modules into executable software modules. To develop a class diagram highlighting the interactions of the user with the system, the team began by identifying the attributes and operations associated with the user asset class. From this, the team was able to identify the required interactions with component MFSA system asset classes. The team proceeded to identify the required attributes and operations associated with each MFSA asset as shown in Figure 31.

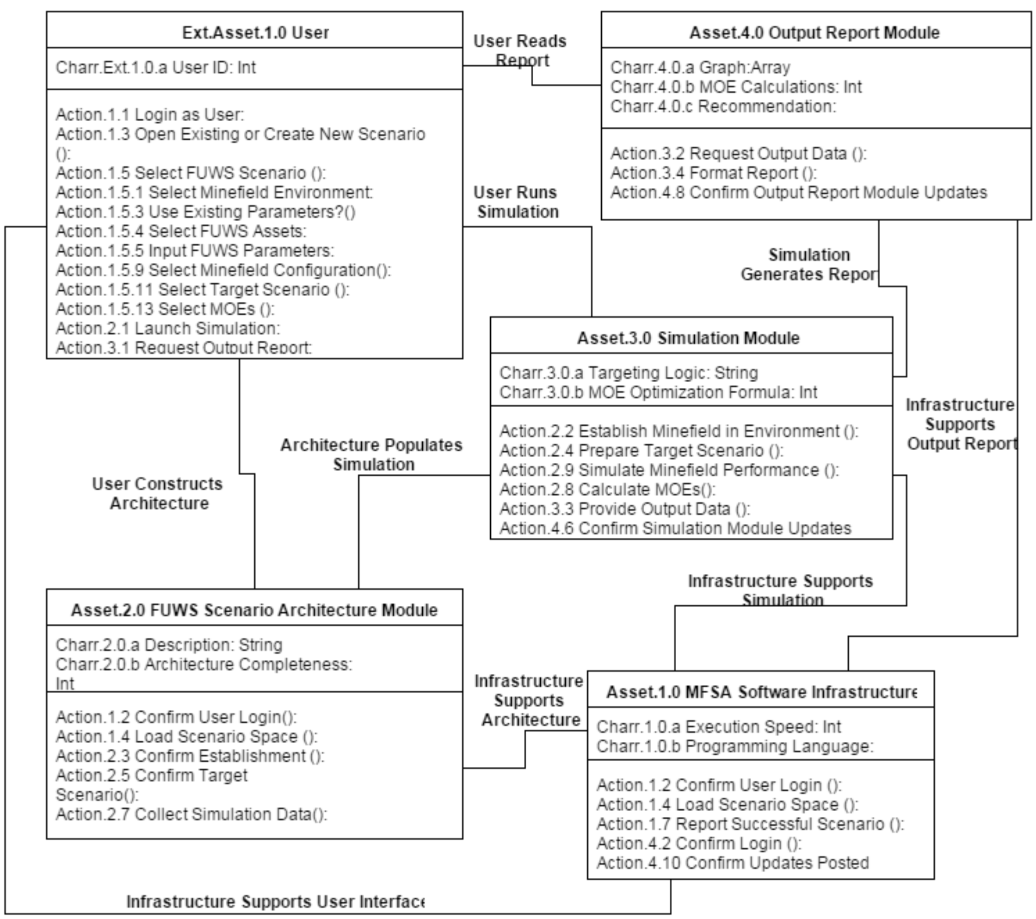


Figure 31. MFSA User Interface Class Diagram

Additional class diagrams developed to describe the interactions of various assets in more detail are provided in Appendix D.

C. FUNCTIONAL REQUIREMENTS ALLOCATION

> The allocated architecture integrates the requirements decomposition with the functional and physical architectures (Buede 2009, 284)

This section describes the team's efforts to decompose top-level requirements and establish traceability with the actions and interfaces in the proposed architectures.

1. Requirements Hierarchy

> A Requirement … identifies a capability, characteristic, or quality factor of a system that must exist for the system to have value and utility to the user. (LML 2013, 12)

As part of the MFSA architecture model development, the identified requirements were arranged in a hierarchy, shown in Figure 32.

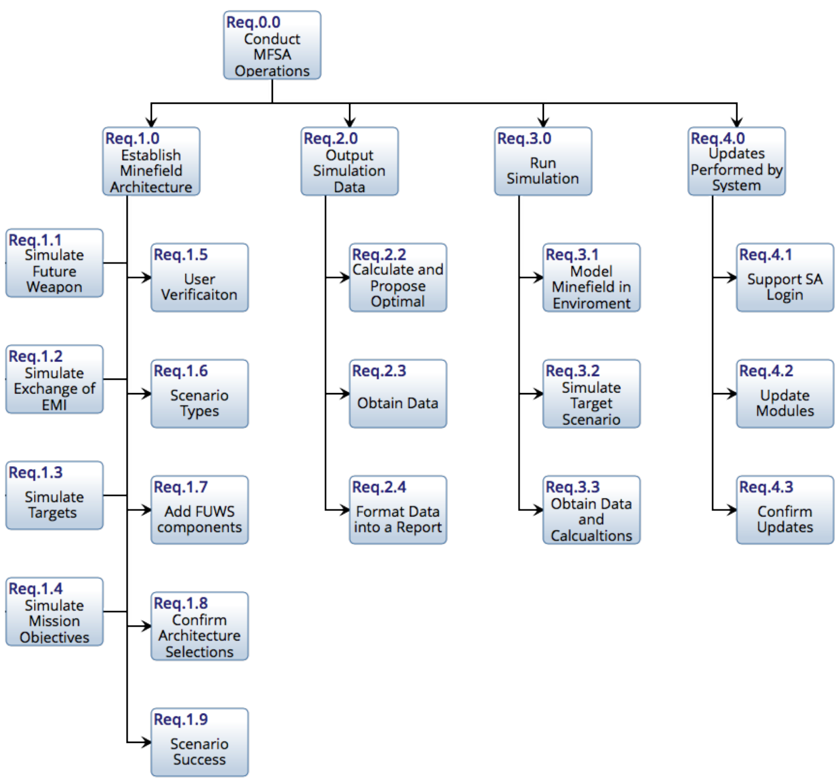


Figure 32. MFSA Requirements Hierarchy

The input and output requirement identified in Chapter III are augmented by additional requirement discovered during the architecture development process.

2. Requirement Allocation

The team used SysML Requirement Diagrams to trace requirements to architecture elements that implement the requirements. The allocation of top-level requirements can be seen in Figure 33. The allocation of the decomposed requirements of Figure 32 is provided in Appendix E.

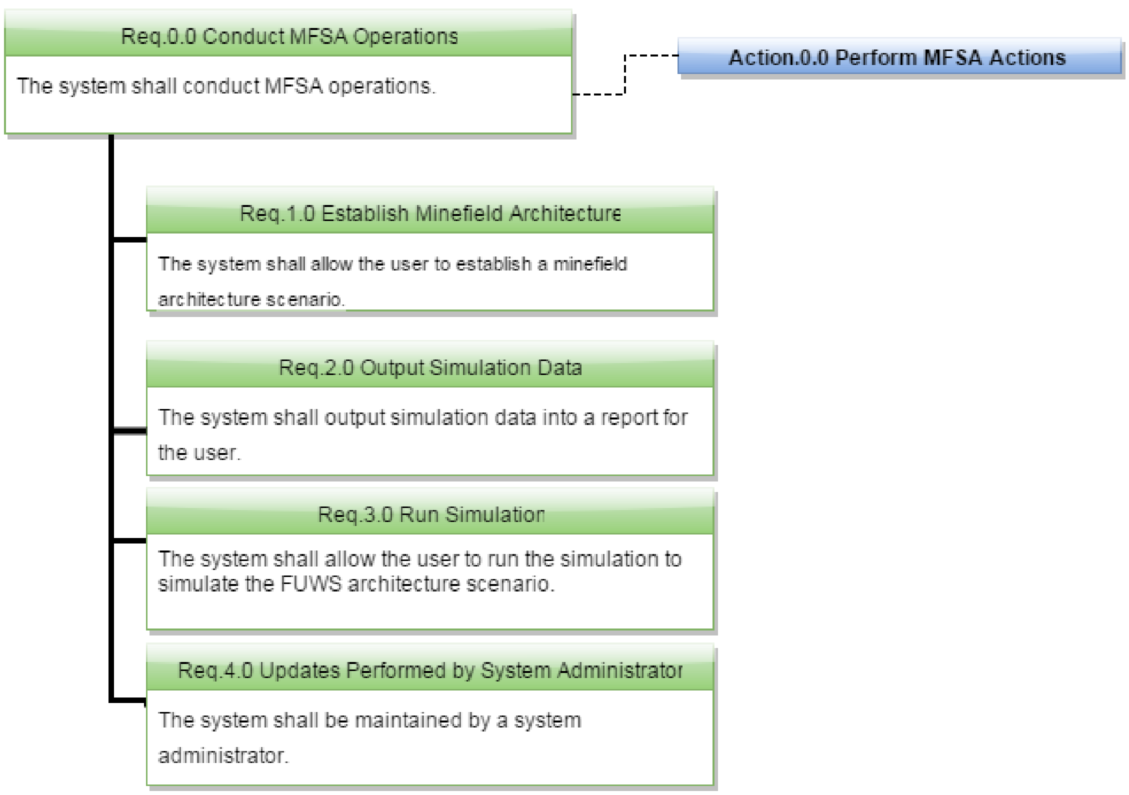


Figure 33. High Level Requirement Diagram

D. SPECIFICATION MATCHING

> If specification matching points to an existing component that fits the needs of the current application, you can extract the component from a reuse library (repository) and use it in the design of a new system. (Pressman 2015, 312)

As discussed in Chapter II.C, the team reviewed GAMET capabilities as part of the capability gap analysis. During this review, the team identified a number of capabilities provided by GAMET that would be appropriate for reuse in the MFSA architecture. The reuse of appropriate capabilities streamlines development efforts and by using proven solutions, potentially reduces validation and verification efforts.

1. Dual User Modes

GAMET employs of two user modes: Analysis Mode and Planning Mode. In Analysis Mode, the user defines the number of nodes in the field in order to evaluate the minefield's effectiveness. In Planning mode the user defines the desired effectiveness and GAMET automatically determines the number of nodes necessary to achieve the effectiveness (Belton 2015, 2). The Mental Focus team re-applied this basic architecture of two user modes to ensure the system provided capability to both the program analyst and operational planner.

2. AUWS Upgrades

As discussed in Chapter II.C, GAMET was upgraded to provide limited AUWS simulation capability. To support AUWS simulation, GAMET was modified to include communication logic algorithms between sensor and weapon nodes. This modification was extended to include probabilistic determinations of successful communication and user selectable decision logic options (Belton 2011, 10). To support evaluation of the energy requirements in various AUWS configurations, GAMET was also modified to include energy usage parameters. GAMET accounts for total energy consumption, energy consumed per detection, and energy consumed per message transmission (and receipt) at various power levels (Belton 2011, 19). The evaluation of energy requirements directly

supports evaluation of FUWS design alternatives. These and other AUWS directed upgrades were incorporated for reuse in the MFSA concept.

3. Graphical User Interface

GAMET includes a graphical display that provides the user a visual representation of the minefield being simulated. This allows the user to visualize the simulation and provides increased user understanding of the capability under consideration. This also allows the user to capture graphics and images that can be used in operational planning and capability development briefings as appropriate (Belton 2015, 20).

THIS PAGE INTENTIONALLY LEFT BLANK

VI. PROTOTYPE DEVELOPMENT

> Models attempt to represent the entities of the engineering problem (opportunities) and their relationships to each other and connect them to the proposed solution or existing mechanism that addresses the problem. The model used in this way is the centerpiece of MBSE. (Long and Scott 2011, 32)

One of the team's goals (Section I.D.3, Goal 4) was the development of a prototype simulation system (included at Appendix G) that demonstrated the team's solution approach. This prototype proved beneficial in developing a more thorough understanding of the emergent behaviors of a distributed sensor system evaluating the performance differences from a legacy mine system. Given the limited resources available, the Mental Focus team chose to execute the prototype development as the first demo in a scrum[14] development process. To simulate this agile software development technique, the team conducted short semi-weekly meetings to brainstorm techniques, assign responsibilities, and track progress. During the second in-progress review (IPR) the team presented the prototype for "customer feedback" from attending faculty and students. In response to this feedback, the prototype was updated to incorporate additional outputs desired by potential users.

A. METHODOLOGY

> A primary reason for the popularity of agent based modeling (ABM) and its departure from other simulation paradigms is that ABM can simulate and help examine organized complex systems (OCS). This means the ABM paradigm can represent large systems consisting of many subsystem interactions. (Heath et al. 2009)

The team began the prototype development process by selecting a simulation environment for use. The team considered a number of programs, conducting a brief analysis of alternatives detailed in Appendix F, before selecting Netlogo[15] for use. Unlike

---

[14] Scrum is an agile software development method conceived by Jeff Sutherland in the 1990s. Development work is conducted in sprints that deliver demonstrations of functionality to the customer for evaluation (Pressman 2015, 78–79).

[15] Netlogo is a free, open-source modeling environment developed and maintained by the Center for Connected Learning and Computer-Based Modeling at Northwestern University.

the other programs considered, Netlogo is an agent based modeling (ABM) platform. While not considered in the initial selection of Netlogo, the team discovered that the ABM approach is well suited to the simulation of a FUWS. Model-Based Systems Engineering (MBSE) traditionally uses architecture models to decompose and allocate the required system functional behaviors using various process models[16] to manage the complexity of the design (Buede 2009, 60). In contrast, ABM, much like object orient programming, begins with the definition of agents or assets and their attributes. When providing the agents with decision-making rule sets, ABM becomes a very capable technique for simulating the actions and interactions of large numbers of "like" agents, such as the sensors and weapons in a FUWS.

1. Notation

> Every modeling technique is a language used to represent reality so that some question can be answered with greater validity than could be obtained without the model. (Buede 2009, 59)

Netlogo primitive agents are grouped into four distinct agent-sets:

1. The *observer* is a single agent that observes and directs the actions of other agents in the model.
2. *Patches* are fixed background agents that form the environment on which other agents act.
3. *Turtles* are agents that can move, interacting with both patches and other turtles.
4. *Links* are agents that connect turtles, establishing an enduring relationship between two turtles

Subsets of these primitive agent-sets can be established by creating "breeds" of turtles or links with custom attributes and by "asking" groups of agents about their parameters, including relationships with other agents. This allowed the programmer to

[16] The Enhanced Function Flow Block Diagram (EEFBD), ICAM Definition for Function Modeling (IDEF0), N^2 Diagram, SysML Sequence Diagram, SysML Activity Diagram, and LML Action Diagram all decompose functional behavior (Long and Scott 2014, 39–44) by tracing the processing of energy, matter, material wealth and information (EMMI) through the system.

develop simple, condition based behavior heuristics and apply them to large numbers of agents, simplifying the model development process.

2. Scrum Backlog

The scrum development process uses a *backlog* to track the user functions targeted for development in the sprint. To scale and prioritize the development of requirements identified in Chapters III and IV, the team developed the following simulation goals for the prototype structured using the decide, detect, deliver, assess (D3A) targeting methodology used by Maritime Component Commanders (JP 3–60, C-1) and shown in Figure 34.

1. Decide. The prototype would allow the user to *decide* to employ either a legacy mine capability or FUWS. The simulation would support this decision by simulating the deployment of the selected capabilities in a two-dimensional counter-mobility area using selected algorithms.

2. Detect. The prototype would simulate sensors capable of *detecting* the proximity of a hostile contact.

3. Deliver. The prototype would simulate weapons capable of *delivering* mission kill effect. This includes simulating explode-in-place weapons in a legacy architecture and intercept-to-engage weapons in a FUWS architecture.

4. Assess. The prototype would calculate system MOPs for *assessment* by the user. This would include, at a minimum, the SIT and threat profile.

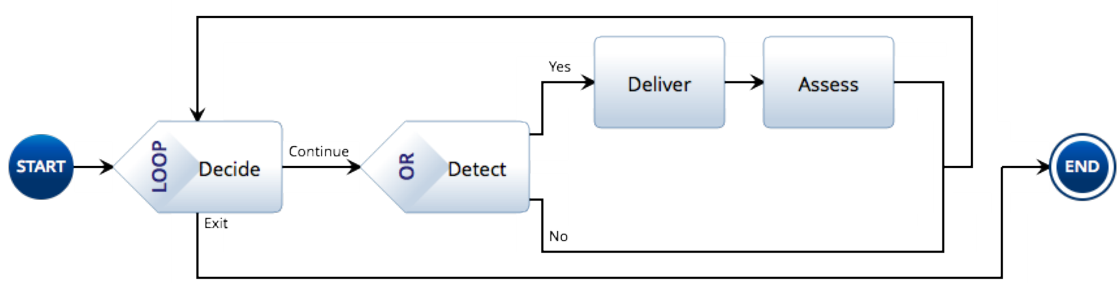


Figure 34. D3A Targeting Methodology.

B. REFERENCE SCENARIO

The team developed a simple reference scenario that could be used to evaluate the effectiveness of counter-mobility architectures. As shown in Figure 35, hostile surface ships approach the western entrance of a maritime straight with the goal of transiting to a point east of the straight. To limit the hostile forces' mobility, the friendly commander deploys a counter-mobility capability in the 10 nm by 10 nm area shown. Multiple surface ships will sequentially attempt to transit the area, requiring the friendly commander to possess a sustained counter-mobility capability.

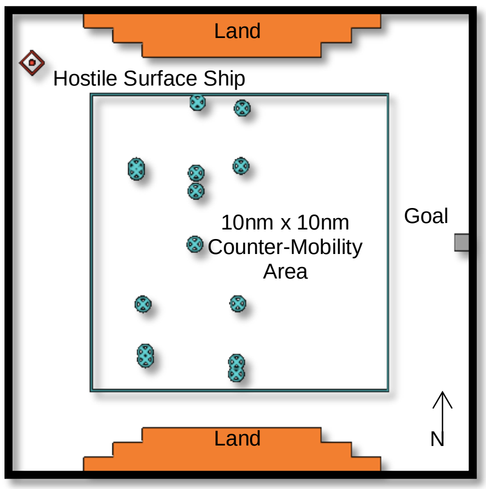


Figure 35. Scenario Laydown

1. Assumptions

> ... it is a mistake to ascribe objectivity to models. Complex mathematical models have subjective assumptions throughout them. (Buede 2009, 60)

The following assumptions were explicitly made in the development of the prototype model to maintain simplicity and demonstrate the selected modeling approach.

1. Hostile contacts do not maneuver within the minefield area

2. Sensor detections can be assumed to occur at a fixed range as opposed to a probabilistic function of target signal strength and sensor sensitivity

3. Sensor false detect rate is low and can be neglected

4. Data latency in the system is low, and can be neglected

5. Warhead detonations within a fixed range always result in a mission kill with no partial damage

With these assumptions, the model results should not be used to predict absolute system behavior but can be used to establish the relative behavior of the solutions under consideration and provide a framework for further development and refinement. The chosen modeling environment is robust enough to support reducing these assumptions and increasing the accuracy of the model in subsequent sprints.

2. Conceptual Model

> ABM begins with assumptions about agents and their interactions and then uses computer simulation to generate "histories" that can reveal the dynamic consequences of these assumptions. Thus, ABM researchers can investigate how large-scale effects arise from the micro-processes of interactions among many agents. (Axelrod and Tesfatsion 2015)

Using a "middle out" engineering approach (Long and Scott 2011, 14), the first solution concept developed was the "as is" naval mine solution. Sensors within a given range of the hostile ship detect the ship and send a signal to the connected, collocated weapon to detonate. If the detonation occurs within the blast radius of the weapon, the system achieves a mission kill and the hostile ship dies.

While the "as is" mine is conceptually simple, the FUWS concept is much more complicated and requires more attributes for the sensors and weapons. In this conceptual model, a sensor network is deployed separate from a number of torpedo batteries. When a sensor detects a hostile ship it informs all sensors within a given communication radius that it has detected a threat. These sensors act as relays passing on the detection of the threat to additional sensors and eventually to the UUV batteries. The "next to fire" torpedo in the network is then aimed based on the location of the detecting sensor and a simplistic targeting logic, assumed hostile ship's course and speed. Once fired, the torpedo loses communication with the network and attempts to gain organic contact on the hostile ship using a forward-looking cone of acquisition. If the torpedo "sees" the

ship, it will home on the ship until it reaches a range where it detonates, killing the ship. If the torpedo fails to "see" the ship, it will eventually run out of fuel and shutdown.

C. COMPUTER MODEL

> There are major advantages arising from using models as the basis of systems engineering. (Long and Scott 2011, 65)

To translate these conceptual models into a functional computer simulation, the team decomposed *Asset 2.2 FUWS Assets* of Chapter V.B and allocated some of the basic input requirements of Chapter III to the asset subclasses. To support the translation of the conceptual design into the Netlogo modeling environment, a UML class diagram, shown in Figure 36, was used to map the FUWS asset components onto the Netlogo primitive agents.

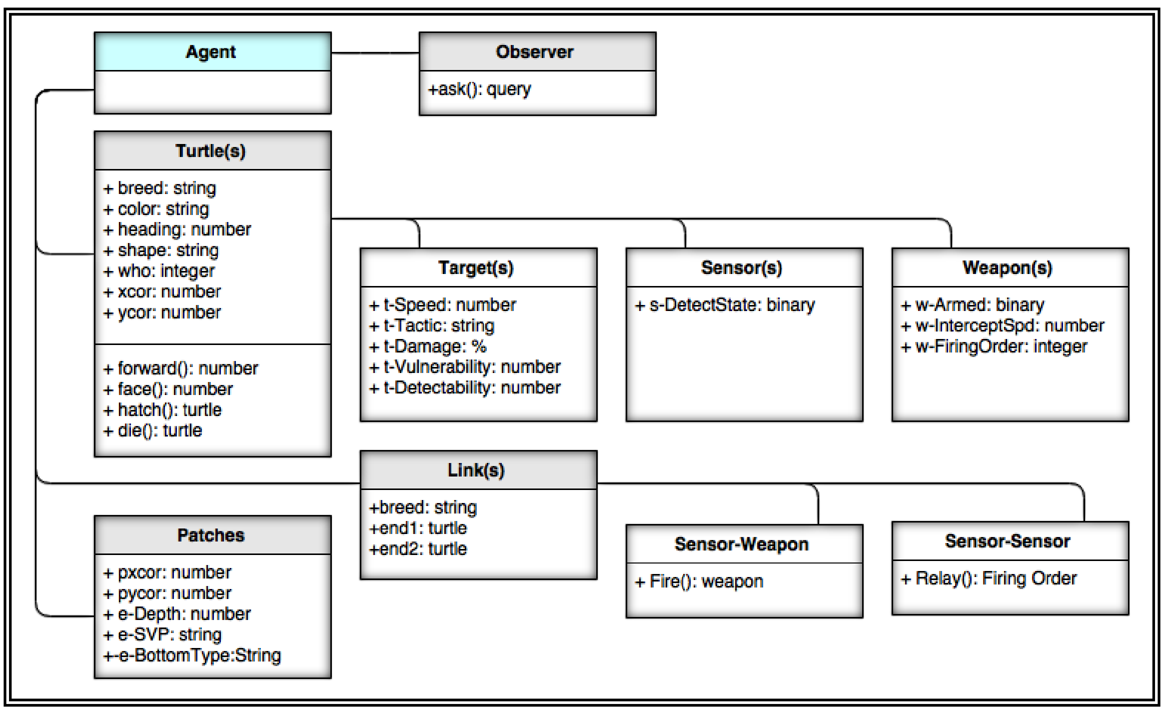


Figure 36. UML Class diagram of Agent Breeds and Attributes

1. User Interface

The prototype computer model user interface is shown in Figure 37 with additional views shown in Appendix G. On the left of the screen are user-selected inputs to the model. The user begins by selecting the desired counter-mobility system architecture and tactics from the *sim-type* dropdown. The *sim-runs* input box sets the number of Monte-Carlo simulation run and the *FixedField* toggle determines if a new randomized undersea weapon system deployment laydown is generated between simulation runs.

To model a legacy minefield, the user selects either a “radial minefield” (mines are laid in lines passing near the center of the counter-mobility area) or a “vertical minefield” (mines are laid in rows across the transit axis) from the *sim-type* dropdown. The user then selects the total quantity of mines and the number of lines in which they are deployed using the *Undersea Weapon System Parameters* slider bars, *Lines* and *MineQty*.

To model a FUWS, the user selects *fuws* from the *sim-type* dropdown. The user then selects the total quantity of sensors (*SensorQty*), the number of lines in which the sensors are deployed (*Lines*), then number of torpedoes (*MobileWeaponQty*) and the number of batteries (*UUVQty*) in which the weapons are deployed using the appropriate *Undersea Weapon System Parameters* slider bars.

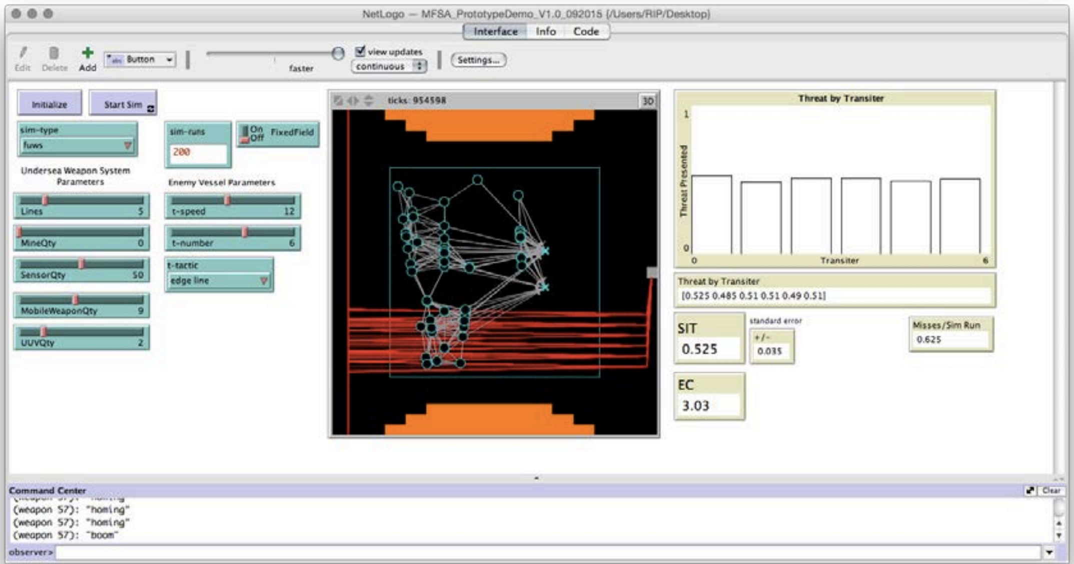


Figure 37. Prototype Demonstration

The user controls the setup and tactics of the threat using the *Enemy Vessel Parameters* slider bars. The *t-speed* slider sets the transit speed of the target vessels and *t-number* sets the number of sequential vessels transiting in each simulation run. The *t-tactic* drop down is used to select the tactic used by the threat vessels: *direct-path* (vessels transit directly from their random points of origin to the goal), *center-line* (vessels transit a 1ky wide path thru the center of the counter-mobility area), or *edge-line* (vessels transit a 1ky wide path randomly selected away from the center of the counter-mobility area).

After setting up the weapon system and threat, the user must click on the *Initialize* button to update the settings in the model and the *Start-Sim* button to begin the series of simulations.

In the center of the screen is a graphic overview of the simulation. Sensors are shown as circles, weapons as exes, and threat vessels as diamonds. In the FUWS mode, the communications network links are shown in grey to support user visualization of the communications network. As the simulation runs, the user can watch the interactions of

the threat with the sensors and weapons, observing the effectiveness of the weapon system and the potential weaknesses of the system.

On the right side of the screen are a number of output MOPs. The bar graph shows the calculated threat presented to each sequential transiting vessel. Point estimates of the simple initial threat (SIT), standard error of the SIT, and expected casualties (EC) are output in the monitor windows below the graph. Also shown in FUWS scenarios are the number of misses (torpedoes expended but that failed to hit) per simulation run.

2. Verification and Validation

Because the prototype simulation system was developed as a demonstration for communication with stakeholders, it was subjected to a limited verification and validation process. System verification was conducted using limited software smoke testing (Pressman 2015, 479) during each programming day. As new features were added, the simulation was debugged and executed to ensure it behaved as expected. System validation was conducted using a beta testing (Pressman 2015, 485) strategy with other members of the Mental Focus team acting as end-users.

3. Results

> Was planned minefield effectiveness achieved at > 50% SIT? (Dept. of the Navy 2007, Performance Metric #2 of task NTA 5.4.3.6 Coordinate Offensive Mining Operations)

The prototype simulation system was developed to demonstrate the team's conceptual solution approach and support additional requirement discovery. The data in the system is generic and not representative of existing or planned systems. As such, the comparison of simulation predictions to real world performance should not be conducted and is outside the scope of this project. Despite these limitations, the prototype simulation system was useful in answering some of the team's initial study questions.

The standard minefield effectiveness metric in current use is the simple initial threat (SIT), or the probability that the first hostile ship to transit the minefield (hostile $ship_1$) is killed (equation 1).

$$SIT \equiv p(\text{hostile ship}_1 \text{ killed}) \approx k_1 / n \quad (1)$$

Where k_1 is the number of times the first hostile ship is killed and
n is the number of scenarios run

While operational planners currently focus on the SIT MOP, looking at how the minefield's performance changes with time provides a more holistic understanding of system performance. By extending the concept of the threat presented by the minefield to the i^{th} hostile ship (equation 2), one can develop a threat profile (T) vs. transit sequence number (i).

$$T_i \equiv p(\text{hostile ship}_i \text{ killed}) \approx k_i / n \quad (2)$$

Another useful metric is the expected casualties (EC) shown in equation 3. EC provides the warfighter with an estimate of the reduction in the enemy force, should the enemy attempt to transit the minefield.

$$EC \equiv E(\text{hostile ship's killed}) \approx \sum k_i / n \quad (3)$$

To highlight the value of the MFSA tool, the team used BehaviorSpace[17] to explore the capability provided by the FUWS parameters described in Table 14 and the legacy mine parameters described in Table 15. By varying the parameters identified (and underlined) in Tables 14 and 15, the team was able to use Monte Carlo simulations of the systems to show the impact on capability performance. Using BehaviorSpace, the team conducted a "sweep" of the parameter space by conducting Monte Carlo simulations for twelve different implementations of both the legacy minefield and the FUWS architecture. The results of these scenarios were post processed in Excel and summary statistics are provided in Appendix H.

[17] BehaviorSpace is a tool integrated with NetLogo that allows users to systematically vary a model's parameters and explore combinations of settings.

Table 14. FUWS Model Parameters

Weapons	Single speed, 45kts, torpedoes with passive seekers having a 45° cone of acquisition and detection range of 2kyds, and with blast radius of N(μ=200 yd, σ=12 yd)
Weapon arrangement	6 weapons distributed on 1, 2, or 3 stationary UUV launchers
Sensor	Networked sensors with detection range N(μ=200 yd, σ=25 yds) against all hostile ships
Total Sensors	50 or 100 distributed in either 2 or 5 vertical lines
Communicators	Sensor-sensor communications ranges of 4kyds and sensor-UUV communication ranges of 10kyds with negligible data latency. The communicators pass the geographic location of a detecting sensor.

Table 15. Legacy Mine Model Parameters

Weapons	Explode in place warheads with blast radius: N(μ=200 yd, σ=12 yd)
Weapon arrangement	50, 60, 70, 80, 90, or 100 mines distributed in either 5 or 10 "Vertical" mine lines
Sensor	Integrated sensor with detection range N(μ=200 yd, σ=25 yd) against all hostile ships

Figure 38 shows the resulting threat profile estimate for each configuration with FUWS data points plotted in green and legacy mine data points plotted in blue. While the independent variable is not time, the sequential nature of the hostile ships transiting the field provides a proxy that allows us to show system performance trends without focusing on the single system metric of SIT. The arrows show the general shape of the data series associated with each architecture configuration. While the legacy mines present a

capability that decays exponentially,[18] the FUWS provides a nearly static capability that only begins to decay as the number of threat ships approaches the number of weapons in the system.[19] As a result, while all the system configurations modeled begin with a SIT between 0.4 and 0.8, by the arrival of the third transiting vessel, the FUWS systems are significantly out performing legacy systems. The change in the shape of the performance data is significant and addresses the second study question (Chapter I). The change in the threat profile indicates that the FUWS will sustain its performance while weapons remain in the system and is an emergent property of the FUWS architecture.

> Systems thinkers use graphs of system behavior to understand trends over time rather than focusing attention on individual events. (Meadows and Wright 2008, 20)

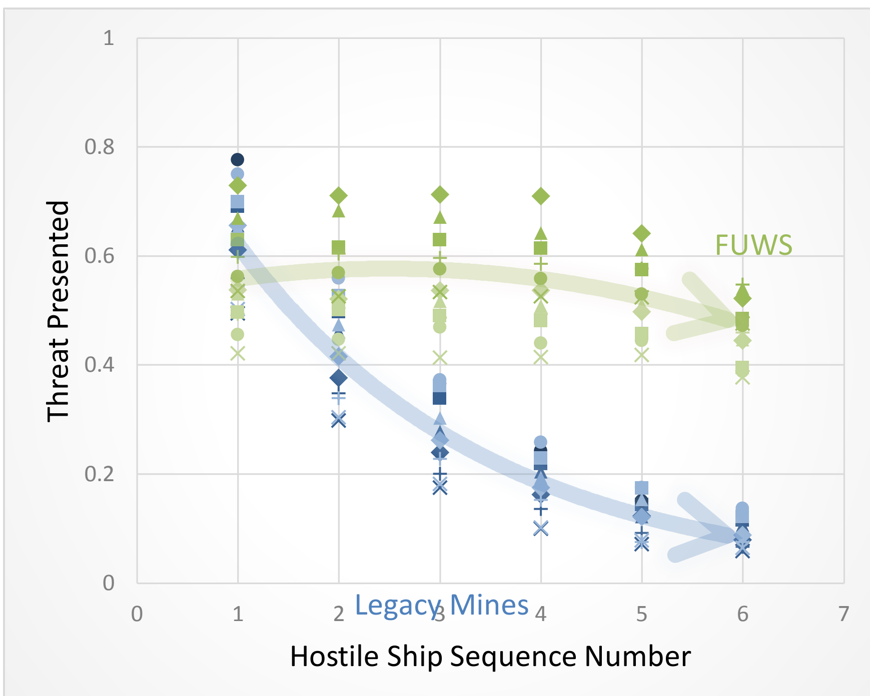


Figure 38. Threat Profile

[18] Fits of exponential decay curves ($y=ae^{-bx}$) to of each of the legacy twelve systems resulted in an average R^2 value of 0.987, with a minimum of 0.971, indicating that the simulation results show an exponential decay of capability.

[19] The best fit curve to the FUWS data was a second order polynomial ($y=ax^2+bx+c$) with a "maximum" near the first or second transistor and an average R2 value of .881, with a minimum of 0.687. The fit coefficients indicate that the curves to a good job of describing the shape of the performance data.

Also of note, the team observed a strong linear relationship between the SIT and the components of the threat profile. As seen in Figure 39, the single parameter of SIT is a strong indicator for the T_2. This linear relationship holds for T_3 thru T_6. Also, since EC is the sum of threat profile componets, EC could also be expressed as a function of the SIT (Figure 38). As such, the team began to understand the predominance of the SIT in current minefield planning doctrine and measure. Within the legacy architecture, the threat profile and EC are redundent measures to the SIT. However, when comparing the FUWS architecture to the legacy architecture, the SIT is not adequate to describe the change in capability.

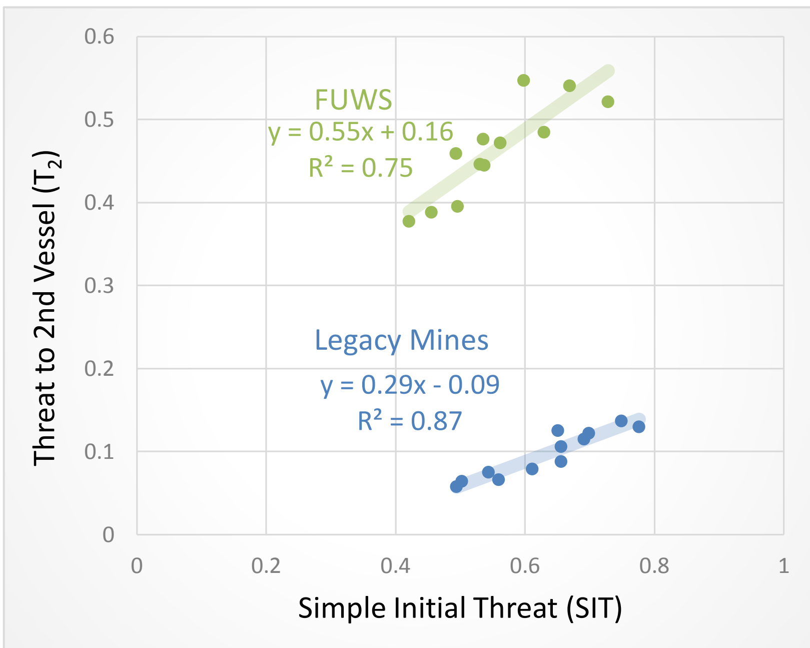


Figure 39. T_2 as a Function of SIT

One can readily see from Figure 40 that using the predicted SIT to compare a legacy mine system to a FUWS does not adequately describe the differences in performance. For example, the FUWS system with a SIT of 0.42 has a predicted EC of 2.5 ships and outperforms the legacy system with a SIT of 0.78 and an EC of 2.2 ships. Note that the FUWS curve is above the legacy curve, indicating a higher EC for a given SIT, and has a steeper slope than the legacy curve, indicating that this difference is more

pronounced at higher SIT values. Since the EC is operationally relevant to the Naval Warfighter, translating into an expected reduction in enemy capability, the team contends that EC should take precedence over SIT, especially when comparing different FUWS architectures.

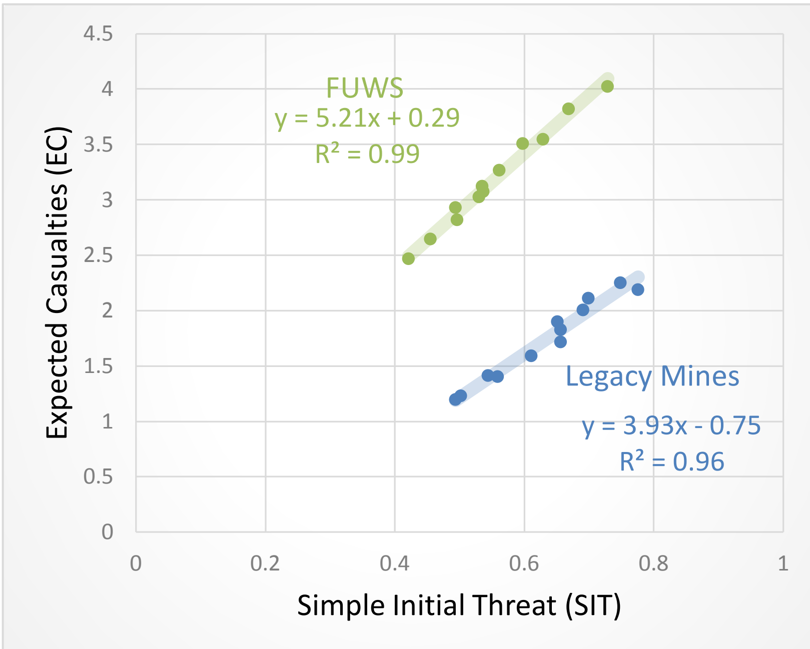


Figure 40. EC as a Function of SIT

4. Cost Benefit Analysis

Finally, to demonstrate the value of MFSA to program analysts, the team developed a rough order of magnitude life cycle cost (LCC) model (Equations 4 and 5) and compared the cost effectiveness of the various solutions in current year dollars (CY$).

$$LCC_{mines} = M \times (C_{procurement} + C_{sustainment} + C_{recovery} + C_{disposal}) + ML \times C_{deployment} \qquad (4)$$

Where M is the number of mines deployed in the minefield
$C_{procurement}$ is the mine procurement cost in CY$ (assumed $1,000/mine)
$C_{sustainment}$ is the average mine sustainment cost in CY$ (assumed $1,000/mine)
$C_{recovery}$ is the average mine recovery cost in CY$ (assumed $10,000/mine)
$C_{disposal}$ is the average mine disposal cost in CY$ (assumed $1,000/mine)
ML is the number minelines and
$C_{deployment}$ is the average cost to deploy a mineline in CY$ (assumed $10,000/line)

$$
\begin{aligned}
LCC_{\text{FUWS}} = {} & W \times (C_{\text{W.procurement}} + C_{\text{W.sustainment}} + C_{\text{W.disposal}}) \\
& + UUV \times (C_{\text{UUV.deployment}} + C_{\text{UUV.recovery}}) \\
& + S \times (C_{\text{S.procurement}} + C_{\text{S.sustainment}}) + SL \times C_{\text{S.deployment}}
\end{aligned}
\tag{5}
$$

Where W is the number of weapons deployed in the minefield
$C_{\text{w.procurement}}$ is the average weapon procurement cost in CY$ (assumed $100,000/weapon)
$C_{\text{w.sustainment}}$ is the average weapon sustainment cost in CY$ (assumed $1,000/weapon)
$C_{\text{w.disposal}}$ is the average weapon disposal cost in CY$ (assumed $1,000/weapon)
UUV is the number of UUV weapon batteries deployed
$C_{\text{UUV.deployment}}$ is the LCC/deployment of a UUV in CY$ (assumed $100,000/UUV)
$C_{\text{UUV.recovery}}$ is the cost to recover a UUV in CY$ (assumed $10,000/UUV)
S is the number of sensors deployed
$C_{\text{s.procurement}}$ is the average sensor procurement cost in CY$ (assumed $1,000/sensors)
$C_{\text{s.sustainment}}$ is the average sensor sustainment cost in CY$ (assumed $1,000/weapon)
SL is then number of sensor lines and
$C_{\text{s.deployment}}$ is the average cost to deploy a sensor line in CY$ (assumed $10,000/line)

To support subsequent analysis, the costs were then normalized to a scale of "0" (20% higher than the highest calculate cost) to "1" (20% lower than the lowest cost calculation). While very rough estimates, these cost models enabled the team to demonstrate the value of MFSA in an acquisition analysis of alternatives. Figure 41 shows a plot of SIT as a function of the normalized LCC for each alternative considered. From the graph, one can see that the FUWS and legacy architectures provide competitive levels of performance at the same general cost levels; that is the alternatives from both architectures are clustered together. However, for a given cost, the maximum SIT performance, shown by the Pareto Frontier, is dominated by legacy solutions sets.

The team also performed this analysis using EC as the discriminating performance parameter. As seen in Figure 42, the FUWS architecture and legacy architecture are no longer grouped, with the FUWS architecture providing significantly improved performance and dominating the Pareto Frontier.

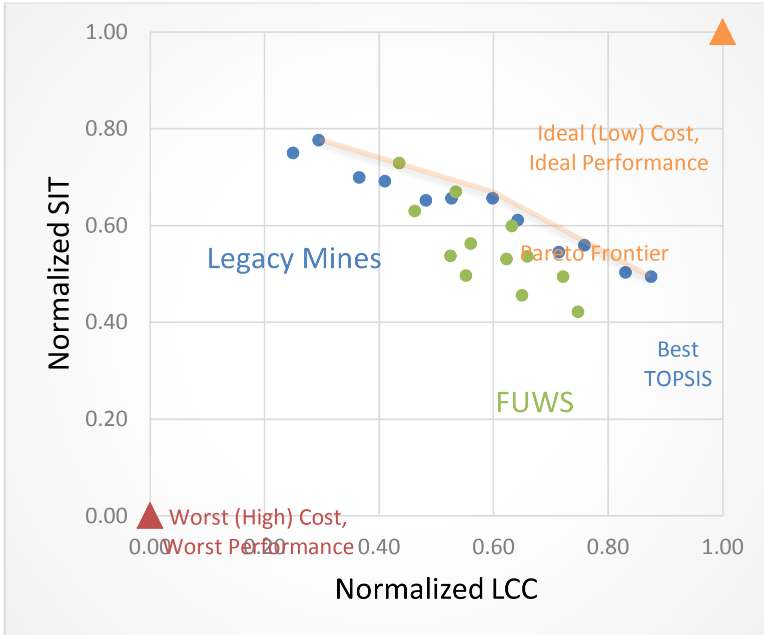


Figure 41. SIT Performance vs Life Cycle Cost

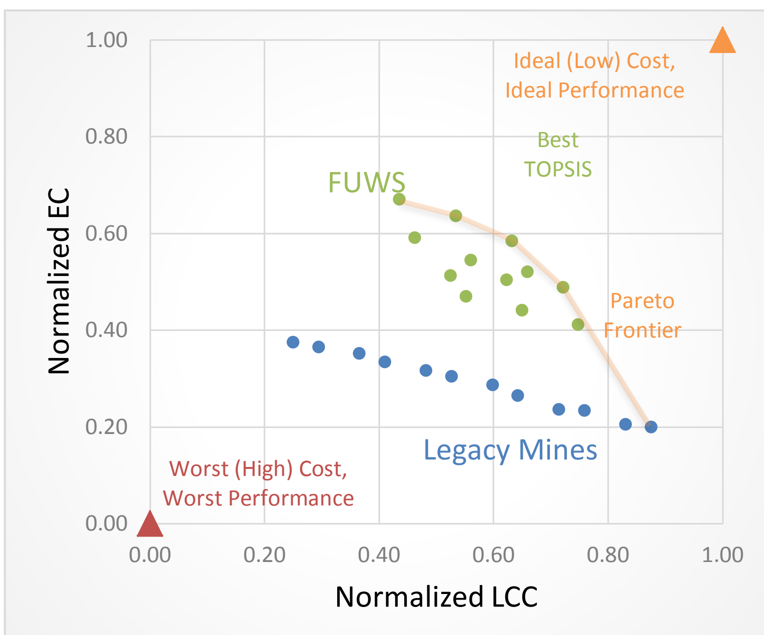


Figure 42. EC Performance vs Life Cycle Cost

Calculating a *Technique for Order of Preference by Similarity to Ideal Solution* (TOPSIS) score for each alternative, as shown in equation 6 using the SIT, indicates the "best" solutions are legacy mine solutions. The top scores are for the legacy solutions with 50 or 60 mines. From this we can see that traditional measures of performance would bias towards the legacy solution architecture.

$$TOPSIS_i = \frac{\sqrt{KPP_i^2 + LCC_i^2}}{\sqrt{KPP_i^2 + LCC_i^2} + \sqrt{(1 - KPP_i)^2 + (1 - KPP_i)^2}} \tag{6}$$

Where KPP_i is either the SIT or normalized EC of the i^{th} alternative and
LCC_i is the normalized cost of the i^{th} alternative

Calculating TOPSIS scores using the normalized EC indicates that FUWS systems provide the "best" solutions. As discussed earlier, the Mental Focus team considers EC a more relevant operational metric that should be considered and emphasized in the development of future counter-mobility capabilities.

THIS PAGE INTENTIONALLY LEFT BLANK

VII. CONCLUSION

> Modelers can give instructions to hundreds or thousands of “agents” all operating independently. This makes it possible to explore the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from their interaction. (Wilensky 2015)

The Mental Focus project team successfully developed a system architecture and requirements model for the development of a simulation system, consistent with the prime objective mission statement articulated in Chapter I: “Analyze and compare system configurations to inform the development and employment of distributed sensors and networked effectors in the undersea environment.” By developing a prototype of the required simulation system, the team was able to conduct an analysis comparing the performance of various system configurations and validating the conceptual solution. By answering the study questions developed during the initial project proposal, the team was able to demonstrate the success of the project and identify areas for future study and continued development.

A. SUMMARY OF WORK

> Simulation differs from standard deduction and induction in both its implementation and its goals. Simulation permits increased understanding of systems through controlled computational experiments. (Axelrod and Tesfatsion 2015)

Using a combination of traditional Systems Engineering, Model-Based Systems Engineering, and Software Engineering practices, the project team analyzed stakeholder needs, established mission scenarios, determined functional and nonfunctional requirements, developed a proposed system architecture and built a demonstration model of the system.

1. Study Question Answers

1. What capabilities does a networked sensor-weapon system provide over the existing legacy mine capability?

The team employed the demonstration model to address this question in Chapter VI. The team was able to show that FUWS provides a potentially significant improvement in EC when compared with legacy capabilities with comparable SIT performance metrics. While the predicted SIT was similar for both architectures, the FUWS minefield presented a sustained capability to subsequent transiting vessels that the legacy systems did not. This threat profile prevents the enemy from forcing a channel through the minefield with a few sacrificial ships. While counter-countermeasures, such as ship counting techniques, could be used to “flatten” the legacy threat profile, they do this by shifting the threat from the initial transiting vessel to subsequent vessels. To restore the SIT and achieve the EC promised by the FUWS architecture requires deploying significantly more mines.

2. What emergent behavior results from modular networks of sensors and weapons?

The team employed the demonstration model to address this question in Chapter VI. Even with the simple model used in the demonstration, the team was able to highlight critical system behaviors that emerge from FUWS’s distributed network of sensors and weapons. The planned emergent behavior is the counter-mobility capability provided by the integration of sensors, communicators and weapons in the FUWS. However, the most significant unforeseen emergent behavior is the change in the threat profile predicted in Chapter VI.

With the legacy approach, the effectiveness of the minefield decays as additional vessels enter the minefield. As the enemy forces a passable channel through the minefield, only a small fraction of the weapons are actually employed before the enemy’s movements are no longer restricted and the counter-mobility capability is lost. This is seen in the exponential decay of the threat profile as the enemy forces through the area (Figure 38).

With the FUWS approach, the effectiveness of the minefield is maintained as vessels enter the minefield. As the enemy attempts to force a channel through the minefield, a significant fraction of the deployed weapons can be brought to bear, regardless of the selected path. This results in a flatter, if not truly constant, threat profile. The team noted that a second order polynomial fit could describe the predicted threat profile, as the capability would begin to degrade as the number of vessels began to approach the number of weapons deployed. While the minefield's predicted threat to the first vessel was similar in both the legacy and FUWS minefields, the predicted threat to subsequent vessels was significantly higher in the FUWS approach. This threat, of course, begins to taper as the number of vessels approaches the number of weapons in the FUWS and collapses when the number of weapons is exceeded. The FUWS would need to be re-enforced to maintain the capability, much as a minefield would need to be re-seeded to reestablish lost capability.

While the demonstration prototype makes a number of simplifying assumptions, the team found this change in behavior and the associated improvement in predicted effectiveness profound enough to recommend further development of MFSA. A more robust MFSA simulation system would provide a better understanding of emergent behaviors, support understanding of the system's performance capabilities, and improve both minefield planning and the development of future minefield capabilities.

3. What are the necessary sequences of events that must be modeled in a FUWS architecture to simulate mission scenarios?

The project team chose to address this question in two ways. The team began by constructing use cases (Chapter III) that would assist in understanding the end-to-end sequence of events from data input to information output. In Chapter V, the team showed, using sequence diagrams, the necessary sequence of events that would be required for the user to define the desired FUWS architecture and operational scenario, the simulation of the architecture, and the output of results to the user. The team also acknowledged that sequence of events in the FUWS detect-to-engage sequence could be decomposed to various levels of complexity. As such, in Chapter III the team identified the data

necessary to model the FUWS architectures at basic, intermediate and advanced levels of complexity to support user accuracy requirements.

The team also addressed this question by developing a demonstration prototype that would simulate a basic mission scenario. This aided the team in understanding the expected sequence of events both in the FUWS and in the MFSA simulation of the FUWS. The team was able to use the process of prototype system development to provide feedback to requirement identification efforts and assist in requirement discovery.

4. What parts, if any, of existing models or simulation systems for undersea warfare could be reused or integrated into MFSA?

In the early phases of this capstone effort, the project team conducted a thorough literature review including an examination of current advanced mining efforts as well as current modeling and simulation efforts.

As described in Chapter II, the team reused components from the AUWS architecture models developed by the SEA17B Capstone team with minor changes and adaptations. The Mental Focus project team used this instantiation of a future mining system and generalized it to develop the FUWS concept. By leveraging the SEA17B capstone team's efforts, the Mental Focus team was able focus on the development of MFSA. This supported for a cohesive continuation of study on the topic of unmanned undersea weapon systems.

The team also identified simulation system components and elements for reuse in the MFSA simulation system. In Chapter V, the team discussed components of the legacy system, GAMET, that could be incorporated in the MFSA simulation system. These elements include features of the graphical user interface, the sensor and communicator logic parameters, and the dual user modes. Reusing these elements allowed the team to focus the System Engineering efforts on other aspects of the system development. Ultimately, the team's analysis of GAMET capabilities and weaknesses was instrumental in the development of a cohesive MFSA conceptual design.

2. Goals Achieved

1. Apply Model-Based Systems Engineering (MBSE) principles to the development of the MFSA architecture conceptual design.

The project team relied heavily on MBSE in two primary lines of effort. The first was the use of Innoslate to develop the architectural model described in Chapter V. The second was the use of NetLogo and Agent Based Modeling to develop the prototype model described in Chapter VI. The successful application of MBSE to these efforts enabled the accomplishment of subsequent goals. MBSE allowed the project team to better examine the functionality of the system and understand the impacts of system elements on system requirements.

2. Identify requirements for the MFSA conceptual architecture.

The project team identified the functional requirements (Chapter III), non-functional requirements (Chapter IV), and developed a conceptual architecture implementing these requirements (Chapter V). In the functional analysis, the team analyzed the purpose of the system and required outputs that would support fulfillment of that purpose. The team then developed a set of input requirements that would be required to produce the desired outputs. These inputs, described in more detail in Appendix C, provide the data about the system under consideration (the sensors, communicators and effectors that comprise the weapon system), the threat and the environment in which they operate. With these inputs, the simulation system can provide the user with the required system performance information to support alternative design and operation employment decisions.

The team also conducted an analysis of non-functional requirements that would add value to the user experience and support the functional employment of the system. Both the functional and nonfunctional requirements were utilized in the development of the proposed conceptual system architecture.

3. Develop model(s) that represent the sequence of targeting and decision events in a mining scenario from sensing the presence of a vessel to engaging a threat.

The team used Innoslate to support the development of an architectural model of the proposed MFSA system as described in Chapter V. This allowed the team to develop a mature, cohesive system architecture model. Innoslate evaluates the maturity based on a number of pass-fail statements in five different categories: Decomposition, Traceability, Action Performance, Input/ Output and Connections.

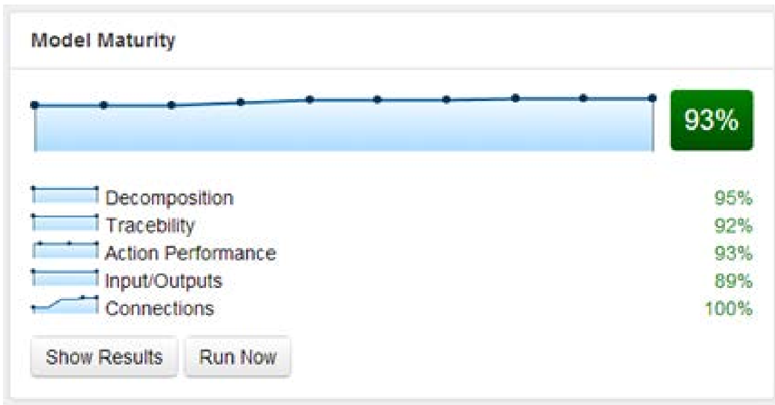


Figure 43. Innoslate Model Maturity Tracker

The process of model development and the discipline required to develop a mature architectural model aided the team in the discovery of the functional requirements. As seen in Chapter V and Appendix E, the process of developing the functional and structural architectures helped the team identify requirements not directly linked to the system inputs and outputs.

4. Develop a prototype simulation system to demonstrate the conceptual architecture and to support requirement discovery.

The project team developed a prototype simulation system in NetLogo to demonstrate the conceptual architecture to stakeholders and support additional requirement discovery. The team defined the relationships and interactions between sensors, communicators, weapons and the threat using NetLogo's Agent Based Modeling environment. The process of prototype development also supported the requirement analysis in Chapters III and V and the identification of the minimum required detect-to-engage sequence to support FUWS simulation.

While the team made a number of simplifying assumptions to support development of the prototype within available resources, the prototype was able to demonstrate the detect-to-engage sequence of a FUWS and calculate measures of effectives that could compare various FUWS solution approaches. This allowed the team to conduct analysis in Chapter VI comparing the performance of a legacy minefield with that of a FUWS, showing the effectiveness of a FUWS architectural approach and the potential operational and cost benefits associated with the FUWS concept.

5. Investigate which measures of effectiveness are most applicable for evaluating advanced undersea weapons systems.

The team's initial research indicated that the mine warfare community relied excessively on Simple Initial Threat (SIT) measure of performance. This is seen in the paucity of alternative measures of performance specified for minefield planning tasks (Appendix B). Reviews of doctrine indicated that, while other established measures such as expected casualties (EC) and the threat profile were available, they were not emphasized in the evaluation of plans and systems.

The team postulated that these other MOPs were under utilized and investigated their applicability to the FUWS concept. As seen in Chapter VI, the reliance on SIT as a single measure of performance is viable in the legacy architecture as the threat profile and EC are directly related to the SIT. However, the team also showed that these relationships change when the architecture is changed and that a shift in emphasis to the EC in a design scenario may be appropriate.

The team recognized that a system such as MFSA has the potential to leverage the growth in available computing power to compute additional, potentially new, measures of performance and effectiveness and provide these to the user in meaningful ways. As seen in Appendix I, the team postulated that the minefield effectiveness is not uniform and varies across the minefield. Providing this information to the planner can ensure that the weapon system effectiveness is appropriately distributed by the placement of sensors and weapons. This information supports improved minefield planning and informed operational risk decision-making by leadership.

B. RECOMMENDATIONS FOR CONTINUED DEVELOPMENT

Within the scope of this CAPSTONE effort, the team was able to transition MFSA into the conceptual development phase of the system life cycle. The team demonstrated Systems Engineering, Model-Based Systems Engineering, and Software Engineering techniques to describe the system context and the proposed solution system at a high level of abstraction. The expressed need for a MFSA system remains (Ponirakis 2014). Further Systems Engineering efforts are necessary develop and deliver an operational MFSA system. The project team recommends that continued development efforts focus on the following three lines of effort: comparison of alternative MFSA system architectures, techniques to support more sophisticated FUWS targeting logic options, and analysis of the MFSA integration requirements with other warfare planning systems. These recommendations represent critical System Engineering best practices that were not included in the scope of this project.

The Mental Focus team developed a single system architecture to aid in the conceptual understanding of the proposed software system and in the development of system requirements. However, this architecture was not formally evaluated and may not be the most successful or efficient approach. Before transitioning system development to the detailed design phase, a formal analysis of alternatives should be performed on comparative system architectures. This systems engineering analysis should use additional stakeholder input and priorities to develop comparative parameters for MFSA evaluation.

The targeting logic used in the prototype demonstration is very simplistic. The FUWS modeled simply shoots a single weapon at an estimated intercept point down the expected axis of motion from a detecting sensor. Improvements in the sophistication of this targeting logic could dramatically improve the system performance. Additionally, this could support comparisons of alternative strategies such as limited sensors with long ranges developing firing solutions based on changes in bearing rate vs the use of large numbers of short-range sensors developing a solution by tracking sensor activation history. The software engineering efforts to develop targeting logic algorithms could be

incorporated in the robust menu of targeting logics required in an operational MFSA system.

Finally, the team recognized an opportunity to employ MBSE techniques in the integration of MFSA into a larger Systems of Systems. While this integration effort was beyond the scope of this capstone, it would be critical to the successful implementation of a MFSA system. The capability provided by a MFSA system relies on integration with appropriate users, other warfare planning systems, naval doctrine, policy, and logistics support. This integration effort must articulate the value of MFSA to the Navy's mission.

These lines of effort would support transitioning the Mental Focus Simulation Application to the next step in the system life cycle and inform the next generation of undersea warfare systems.

C. RECOMMENDATIONS FOR FUTURE STUDY

> Recent technological advances have led to the emergence of distributed wireless sensor and actor networks (WSANs) which are capable of observing the physical world, processing the data, making decisions based on the observations and performing appropriate actions. (Akyildiz and Kasimoglu 2004, 351)

The Mental Focus team also identified three areas for future study. WSANs are a class of systems, analogous to the FUWS concept, that have been studied over the past decade. While not a "wireless" network, the FUWS consists of sensors and actors (weapons) as nodes in a weapon system network. By applying the understanding gained in the study of WSAN sensor-actor coordination and actor-actor coordination to the FUWS system, the student may be able to identify requirements that support robust and fault tolerant FUWS decision algorithms.

> For ad hoc sensor networks, routing protocols must deal with some unique constraints such as limited power, low bandwidth, high error rate, and dynamic topology, which motivate us to explore routing protocols that are energy efficient, self-adaptive, and error tolerant. (Wu et al. 2009, 282)

This leads to the second area of recommended future study, ad hoc sensor networks. Qishi Wu highlights some of the sensor network requirements that were not explored in the scope of this project. Specifically, the required routing protocols that

support sensor-sensor and sensor-actor exchange of information and coordination. The application of network science to support the development of dynamic, ad hoc network protocols that support sensor and weapon re-seeding through the FUWS deployment cycle would support evaluation of FUWS sustainability requirements.

> A primary reason for the popularity of ABM and its departure from other simulation paradigms is that ABM can simulate and help examine organized complex systems (OCS). This means the ABM paradigm can represent large systems consisting of many subsystem interactions. (Heath et al. 2009)

Finally, the ABM technique used in Chapter VI could be used in MBSE analysis of solution architectures and approaches in other warfare systems. For example, an ABM model could be used to show how an air and missile defense system capability varies with threat axis or is overwhelmed by a particular threat scenario. The simple simulations conducted as part of this project demonstrated the potential power of this approach, especially when integrating large quantities of similar component systems or when validating autonomous rule sets executed by sub-systems. High fidelity Agent Based Models could support additional detailed trade space analysis and inform detailed design priorities.

APPENDIX A: FUWS TASKS AND MEASURES

The Universal Joint Task List (UJTL) and Universal Naval Task List (UNTL) are tools used for articulating mission requirements and for evaluating mission readiness (OPNAVINST 3500.38B). The JCIDS User Manual requires capability requirements to be traceable to universal joint tasks (UJTs) and Service tasks (2015, B-3). This appendix provides a summary of the tasks and the associated measures of performance (M#) identified in the task lists that are traceable to mining operations and to FUWS capabilities. From the descriptions and established hierarchy, one can see that mining capabilities are traceable to the Counter-mobility task at the operational and strategic levels. The following UJTs are quoted from the UJTL at the time of the report. Trailing citations indicate the date the task was last approved or modified by the Director of the Joint Staff.

ST 1.5 Conduct Countermobility. Delay, channel, or stop offensive air, land, and sea movement by an enemy formation attempting to achieve concentration for strategic advantage.

Notes: This task may include actions to shape, at the strategic level, enemy retrograde operations to allow friendly exploitation.

M1	Days	Delay an enemy's operations and movement because of friendly systems of barriers, obstacles, and mines.
M2	%	Of designated forces actually assigned to monitor and enforce friendly strategic barriers to enemy mobility.
M3	%	Of enemy force channeled into an unfavorable avenue of approach by friendly system of obstacles or barriers.
M4	%	Reduction in enemy's logistics flow (to below requirements for offensive action).

(UJT approved 06-MAR-15)

ST 1.5.1 Employ Obstacles. Channelize, delay, disrupt or reduce the enemy and protect friendly forces relative to employment of barriers, obstacles, and mines.

Notes: Before hostilities, barriers, obstacles, and minefields can be used as flexible deterrent options without posing an offensive threat. Should deterrence fail, offensive maritime mining of enemy ports and waters can

constrict enemy seaborne economic war sustainment efforts and reduce enemy ability to safely deploy maritime forces. Similarly, offensive employment of scatterable mines can deny or restrict enemy strategic mobility and sustainability efforts. Strategic barriers, obstacles, and minefields normally are emplaced around an existing terrain feature (e.g., mountain chain or strait) or a manmade structure (e.g., air base, canal, highway, or bridge). Selecting locations and emplacing strategic land and maritime obstacles should be coordinated among multinational forces (MNFs) at all levels. This will preclude limiting friendly operational maneuver; conflicting, duplicative, or divergent operations, and possible fratricide among MNF. Plans that could impact on other theaters should be coordinated to prevent potential mutual interference. This is particularly important for maritime minelaying that could affect strategic movement to or from other theaters. This task may require assessing and planning continuity of operations (COOP) or mission-essential tasks provided specific to contractor support for United States (US) and MNFs.

M1	Days	Delay in construction of strategic systems of barriers, obstacles, and mines.
M2	%	Of locations for strategic systems of barriers, obstacles, and mines surveyed before crisis.
M3	%	Of systems of friendly obstacles and barriers successful in delaying, channeling, or stopping enemy offensive action.

(UJT approved 01-APR-15)

OP 1.4 Provide Countermobility. Conduct countermobility operations to shape enemy maneuver and protect friendly forces.

Notes: Barrier, obstacle, and mine warfare employment is not an end in itself, but is in support of the maneuver plan to counter the enemys [sic] freedom of maneuver. This task may include support to enforcement of sanctions, embargoes, blockades, and no-fly zones.

M1	%	Enemy avenues of approach closed as maneuver possibilities by friendly barriers, obstacles, or mines.
M2	%	Monthly reduction in civil populace opinion of target nation central government.
M3	%	Reduction in estimated potential enemy course of action (COAs) after taking counter-mobility action
M4	%	Of reduction in target nation external trade.
M5	%	Of reduction in target nation gross domestic product.

(UJT approved 17-AUG-15)

OP 1.4.1 Employ System of Obstacles. Restrict enemy maneuver options or create friendly maneuver options.

Notes: This task may include the use of coordinated operational and tactical barriers and reinforcement of natural obstacles. Operational barriers and obstacles may be created by the composite effect of many closely coordinated tactical obstacles or by the reinforcement of natural obstacles to form large terrain or massive obstacles. Demolition (obstacles are created by detonation of explosives) is generally used to create tactical level obstacles. However, it can also be used to create operational obstacles such as the destruction of major dams, bridges, and railways, as well as highways through built-up areas or terrain chokepoints. Constructed obstacles are created without the use of explosives (examples are barbed wire obstacles and tank ditches). Field expedient obstacles (abatis or flame explosive) can provide a quick, effective means for providing a limited offensive and defensive obstacle capability when conventional resources are not available.

M1	%	Of increase in friendly force lines of communications (LOCs) after obstacle emplacement.
M2	%	Of available enemy lines of communications (LOCs) and ports of debarkation (PODs) interdicted by friendly obstacles.
M3	%	Of hostile external surface communication absorbed by other lines of communications (LOCs) after barrier emplacement.
M4	%	Of hostile internal surface communication absorbed by other lines of communications (LOCs) after barrier emplacement.
M5	%	Of reduction in hostile military surface communications after barrier emplacement.
M6	%	Of reduction in hostile overall surface communications after barrier emplacement.
M7	%	Of reduction in potential enemy course(s) of action (COAs) after obstacle emplacement.
M8	Days	Until hostile forces are unable to sustain offensive operations.
M9	%	Of increase in incidence of disease in target nation during quarantine or embargo.

(UJT approved 05-MAY-15)

TA 1.4 Conduct Mine Operations. Conduct mining, to include both sea and land mines.

Notes: Mining is: 1. In land mine warfare — an explosive or material, normally encased, designed to destroy or damage ground vehicles, boats, or aircraft, or designed to wound, kill, or otherwise incapacitate personnel. It may be detonated by the action of its victim, by the passage of time, or

by controlled means. 2. In naval mine warfare — an explosive device laid in the water with the intention of damaging or sinking ships or of deterring shipping from entering an area. The term does not include devices attached to the bottoms of ships or to harbor installations by personnel operating underwater, nor does it include devices that explode immediately on expiration of a predetermined time after laying. May be emplaced by land, sea, or air component forces/ means.

M1	%	Of planned mines emplaced in accordance with the operation plan.

(UJT approved 12-MAY-15)

TA 1.4.1 Conduct Offensive Mine Operations. Conduct the offensive employment of mines.

Notes: Location of mines employed need to be maintained in a database that can facilitate information sharing with host nation, allies, coalition, United States Government agencies, information operations, and nongovernmental organizations for stability, security, transition, and reconstruction operations. This employment is not an end in itself, but is an adjunct to other military capabilities. To conduct the offensive employment of mines at the tactical level to delay, disrupt, and attrit enemy forces and protect friendly forces. Offensive employment of mines can deny or restrict enemy strategic mobility and sustainability efforts. Offensive employment of mines can deny or restrict enemy strategic mobility and sustainability efforts. This task may delay, disrupt, and attrit enemy forces and protect friendly forces.

M1	Hours	To develop plans for mine placement (land and maritime).
M2	Hours	To conduct inventory of available mine types and quantity.
M3	Hours	To identify available maritime mine laying capabilities.
M4	Hours	To identify existing mine fields (if applicable).
M5	Hours	To identify enemy avenues of approach and retreat

(UJT approved 12-MAY-15)

TA 1.4.2 Conduct Defensive Mine Operations. Conduct defensive mine operations to degrade the enemys [sic] ability to maneuver, destroy, and attrit the enemy force.

Notes: This task may support economy of force measures; and to retain key terrain or areas of significant tactical value. In other words, adding depth and time to the operational environment (OE). Minefields can

immobilize and canalize enemy forces by taking advantage of terrain by adding strength and depth to the OE.

M1	%	Of planned mines emplaced in accordance with the operation plan.
M2	Y/N	Was guidance provided regarding control of minefield areas and minefield restricted areas?

(UJT approved 12-MAY-15)

The following Service tasks are quoted from the UNTL.

NTA 1.4 Conduct Counter-mobility. To construct obstacles and employ area denial efforts including mines to delay, disrupt, and destroy the enemy. The primary purpose of counter-mobility operations is to slow or divert the enemy, to increase time for target acquisition, and to increase weapons effectiveness.

M1	Hours	Delay in enemy force movements caused by mines/obstacles.
M2	%	Of enemy forces unable to reach their objective due to obstacles.

(UNTL 2007, 3-B-16)

NTA 1.4.1 Conduct Mining. To use air, ground, surface, and subsurface assets to conduct offensive (deploy mines to tactical advantage of friendly forces) and defensive (deploy mines for protection of friendly forces and facilities) mining operations.

M1	Days	To develop obstacle/mining plan.
M2	%	Of enemy units delayed due to mining.
M3	%	Of enemy units damaged or destroyed due to mining.

(UNTL 2007, 3-B-16)

NTA 3.2.1 Attack Enemy Maritime Targets. To attack sea targets with the intent to degrade the ability of enemy forces to conduct coordinated operations and/or perform critical tasks. This task includes all efforts taken to control the battlespace by warfare commanders, including strikes against high payoff and high value targets, such as missile launching ships and submarines, and other strike and power projection units throughout the theater. This task includes also those efforts taken to undermine the enemy’s will to fight.

M1	%	Of attacking systems penetrate to target to deliver ordnance.
M2	Mins	After target identification to complete attack.
M3	%	Of enemy forces destroyed, delayed, disrupted, or degraded.

(UNTL 2007, 3-B-45)

APPENDIX B: MFSA TASKS AND MEASURES

This appendix provides a summary of the UNTL tasks and the associated measures of performance (M#) that are traceable to the tactical capabilities provided by MFSA. Note that the *quality* of the plan is measured by the SIT and number of mines required. The following Service tasks are quoted from the UNTL.

NTA 1.4.1.1 Plan Minefields. To sequentially develop an integrated plan to emplace minefields which will effectively support the tactical plan. Planning consists mainly of establishing obstacle restrictions at higher-level units and detailed design and citing at lower level units

M1	Days	To develop obstacle/mining plan.
M2	#	Mines to accomplish minefields objectives.

(UNTL 2007, 3-B-16)

NTA 5.4.3.6 Coordinate Offensive Mining Operations. To coordinate offensive mining operations to neutralize opposition maritime firepower and minimize threats to friendly forces.

M1	Hours	To coordinate minefield plan and input to MTO.
M2	Y/N	Was planned minefield effectiveness achieved at > 50% SIT?
M3	Y/N	Was minefield re-seeding considered?

(UNTL 2007, 3-B-90)

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C: MFSA INPUT REQUIREMENTS

The MFSA simulation system fills an information need by transforming data describing the environment, target, and weapon system into relevant outputs describing the weapon system performance. To develop these outputs, MFSA must be provided with inputs of environmental, target, weapon system, and mission data. This appendix provides additional details on the purpose and usage of the inputs requirements identified in Chapter III. In particular this appendix demonstrates the potential effect of a particular input parameter on FUWS performance, and thus the purpose of the input in the MFSA system. Those parameters assigned as "basic" are necessary to the development of a useful performance prediction, those designated as "intermediate" or "advanced" will improve the MFSA prediction accuracy, but will require access to additional data and processing power.

ENVIRONMENTAL INPUT PARAMETERS

Geographic Boundaries: According to the International Law, the locations of mines must be recorded (Doswald-Beck 1995, Art 83 and 84). As such, minefield should have boundaries, which will determine the area of coverage necessary and thus the number of weapons required to achieve the desired level of effect. The geographical boundaries also relate to several other characteristics listed below, which if properly linked to authoritative databases could automate portions of the input process.

Water Depth: While minefields are often visualized in two dimensions, the interactions between the mines and targets occur in three dimensions. Water depth directly impacts the performance and operation of sensors, weapons, communicators, and target vessels. For instance, the depth of explode-in-place weapons is a significant factor in the damage delivered to a particular target. It also impacts the maneuverability and detection capability of mobile weapons such as torpedoes. Shallow water can pose challenges to acoustic communicators as surface and bottom reflections complicate the communication signal path. The movement of the target vessel (particularly submerged targets) and mobile weapons, such as torpedoes, may also be restricted by water depth. In

a basic scenario, a single value, such as average water depth, may be adequate to describe performance, in more advanced scenarios the contours of a bathymetric profile should be used to increase the fidelity of the simulation.

Bathymetric Profile: As described above, water depth is a critical variable for a minefield simulation to consider. The bathymetric profile provides contours of the sea floor, allowing better understanding of how individual system nodes will be affected by the depth at their location and by the potential shadowing of signals in more complex profiles.

Sound Velocity Profile: The speed at which sound propagates through water varies with depth (pressure) and is a function of a number of environmental factors such as water temperature and salinity. The variations in sound velocity affect the path of acoustic signals through the water column and thus the performance of acoustic sensors. In deep water, this can be significant as the acoustic signal transmission is shaped and ducted or isolated by changes in the sound velocity profile.

Current: Strong currents will affect mobile effectors, such as torpedoes, introducing a source of error in both aim point and fuel usage. If the distance from the weapon to the target is substantial, the fire control system must either account for the current or risk missing the target. Additionally, currents can impact torpedo fuel usage, potentially changes the effective employment range of a weapon.

Ambient Noise Level: The magnitude of background acoustic noise in the environment, including natural (wind and biological activity) and man-made (shipping) sources, can interfere with or obscure signals from the target vessel to FUWS acoustic sensors. High ambient noise level could also degrade the effective range of acoustic communications, if used.

Ambient Noise Frequency Range: For advanced simulations, in which detailed technical data is available for relevant system and environmental parameters, the frequency range of ambient noise will support more accurately modeling of system performance. For instance, low frequency ambient noise will have minimal impacts on high frequency acoustic communicators and medium frequency threat signals.

Seismic Background Noise: Seismic sensors use vibrations of the seabed to detect the proximity of vessels. In areas with significant seismic activity, FUWS planners and developers may want to consider the effects of spurious signals generated by natural phenomena.

Bottom Type / Bottom Loss: Bottom type contributes to both the transmission of acoustic signals (hard sand may reflect a signal that is absorbed by soft mud) and the self-burial of system components.

Fixed Obstacles: This optional input serves to account for the signal shadowing of known obstacles, such as oilrigs or wreckages, that could impact placement and/or operation of FUWS components.

Probabilistic Obstacles: This optional input would allow the user to generate obstacles based on an estimated probability of occurrence for a given region. Examples of such probabilistic obstacles include fishing nets, buoys, and biologics that could degrade FUWS performance and operation.

TARGET INPUT PARAMETERS

Number: The number of anticipated targets is required at the basic level to determine the threat profile (probability that n^{th} target is damaged). In advanced simulations, the user may want to configure targeting logic based on the ratio of weapons available to anticipated targets, conserving weapons for high-value or particular targets.

Course: The course describes the path taken by targets through the area, and thus the opportunities for detection and engagement by the weapon system. For mobile weapons the course of the target affects computation of the fire control solution and projected intercept point, the accuracy of which directly impact the success of the weapon.

Speed: The speed of a vessel will affect the acoustic and pressure signals it generates. Also, like course, the speed plays a significant role in the fire control solution and projected intercept point required for successful employment of mobile effectors.

Target Priority: When the number of weapons is limited, it may be desirable to designate high value targets and employ an advanced targeting logic. For example, a high priority target may warrant firing a two shot salvo to maximize the probability of success. Conversely, a low priority target may be allowed to pass by if higher priority targets are detected or anticipated.

Target Mission: The counter-mobility capability attempts to deny threat vessels freedom of movement in or through an area. This implies that the threat vessels have an operational need to maneuver to a destination. The axis of this transit or assumed direction of travel is important because it affects the optimal orientation of the sensors and weapons. In general, fewer sensors/weapons are required when placed in a pattern perpendicular to direction of travel by the target.

Class/Type: The class of target vessel can be linked to a number of the following characteristics, supporting automatic population of appropriate fields from recognized databases.

Length: To cause damage, explosive charges must be detonated in close proximity to the threat vessel, often in ranges of tens to low hundreds of yards from the target. As such, the vessel length, which can be over a hundred yards, can be a significant factor in determining both the damage delivered by a warhead and in the appropriate timing of weapon engagement.

Width / Beam: For an explode-in-place weapon, the vessel width can be a significant characteristic in determining the damage delivered by the warhead. In mobile weapon scenarios, it can be an important factor in determining the probability of a successful engagement.

Draft: Vessel draft can be an important factor in the determination of the damage caused by explode-in-place weapons. It is also a significant factor in determining the susceptibility of a vessel to active acoustic exploitation by active sensors and active homing devices on mobile weapons. Vessel draft also determines the navigable waters in the operating area and the mobility of the target in shallow water.

Max Speed: In advanced simulations, the user may desire to have the target vessel attempt to evade a mobile effector by accelerating and maneuvering. The maximum speed would provide an upper boundary to ensure the target vessel's ability to evade with speed.

Damage Susceptibility: This input provides a measure of the targets susceptibility to various weapons. For basic simulations an average or stochastic susceptibility may be applied to a vessel. Alternatively, in more complex analysis, the susceptibility may be a function of the area of the ship, allowing the simulation to model the mission impact of various target points.

Hull material: Hull material may be related to the magnetic signature of the target as well as damage susceptibility. When these factors are unknown, this input allows a rough estimation of characteristics to support more detailed simulations.

Displacement: Magnetic and acoustic signatures can be positively correlated to the displacement of a ship. When these signatures are unknown, the displacement can provide a simple proxy for estimating them. The displacement can also be used in conjunction with speed and water depth to predict the pressure signal. Finally, larger ships tend to have more reserve buoyancy, and thus can be more survivable.

Magnetic signature: This input parameter is needed to simulate the target's susceptibility to magnetic sensors in both legacy mines and FUWS.

Acoustic signature: The acoustic signature as a function of speed is needed to simulate the target's susceptibility to acoustic and seismic sensors in both legacy mines and FUWS. The acoustic signature could include the frequency distribution in order to support simulation of target classification in advanced scenarios.

Maneuvering tactics: A target vessel may detect and maneuver to evade an incoming torpedo. The anticipated maneuvering tactics of the adversary will influence the lost target tactics implemented by the FUWS. In the case of targets with better torpedo detection capabilities and maneuvering characteristics, the timing of the engagement may become critical to success.

Ship Countermeasures: Ships may employ countermeasures and decoys to mask their signals and disrupt weapon engagements. In more advanced simulations these countermeasures could be simulated by altering ship signatures and stochastically causing false returns to active acoustic sensors.

Countermeasures Tactics: This input would describe the tactics an adversary may use to transit the minefield. It could include attempts to force a channel through the minefield, route and speed selection based on bathymetric information, or mine hunting/sweeping.

Mine Hunting Mission: This parameter describes the probability of success of mine hunting in a given area as a function of time. This could be used by the simulation system to predict the expected delay required by the adversary to clear a safe passage route and to determine the decay of counter-mobility capability performance parameters over time.

Mine Sweeping Mission: This parameter describes the probability of success of mine sweeping a given area as a function of time. As the Mine Hunting Mission parameter, this input could be used by the simulation system to predict the expected delay required by the adversary to clear a safe passage route and to determine the decay of counter-mobility capability performance parameters over time.

MISSION INPUT PARAMETERS

Limited Rules of Engagement: Depending on the phase and nature of the conflict, the rules of engagement may be restricted. For example, under certain circumstances the FUWS may be required to have multiple sensors confirm a single target to ensure it is a valid combatant. In other cases, the system may be allowed to fire on any transiting vessel based on a single data source.

Human "in loop" required: As technology advances to allow greater autonomy of systems, policy decisions may be imposed that require a human to decide to engage a target. The latency required could have major implications on a FUWS effectiveness and this mode would allow those effects to be quantified.

Target Discrimination Required: The ability to simulate the capability of the FUWS to differentiate between various types of potential target vessels is likely to be important to intermediate and advanced simulations. A system's ability to discriminate between types of targets may be desired to reduce risk of collateral damage to non-combatants, or may be desired to reserve weapons for the highest value or most susceptible targets. This mode of simulation would allow the user to understand how performance changed against both high-value and low-value targets.

FUWS INPUT PARAMETERS (SENSORS)

Number, 1 to n: The quantity of a particular type of sensor will determine coverage based on the position and detection range of each sensor. This input is intended to capture each sensor node or unit, which may be comprised of multiple sensors detecting various modalities.

Position: This describes the geographical position of a particular sensor relative to the rest of the field and is necessary for calculation detections and communication neighbors.

Sensor Type: The sensor type input describes the identifying characteristics of a particular node and may represent a package of sensors, which detect multiple modalities. The aggregate performance of this sensor is described by additional inputs.

Probability of Detection vs Range: For simple simulations, or where sufficient data is not available, this may be as simple as a single range with a probability of detection. More accurate simulations would use a table of probability detections at various ranges.

Bearing Accuracy: This input would be simulated as errors in the bearing passed from sensors would support simulation of the errors in weapon aim points.

Reliability: Sensor reliability would be used to simulate failure rates and its impact on system performance in more advanced simulation.

Timing: In advanced simulation, precision timing information could be used to support integration of data from multiple sensors, rapidly localizing the threat vessel.

Endurance/Power Usage: Energy is a resource consumed by every action of the sensors. Simple simulation may assume a constant value or to time to energy exhaustion. More advanced simulations may benefit from the additional detail provided by simulating the power usage to process a contact detection and the consumption based on data sampling rate.

FUWS INPUT PARAMETERS (COMMUNICATORS)

Range: The range at which sensors and weapons are able to communicate is critical in establishing the nodes to support a robust network architecture.

Data rate: The data rate limits the speed of communications between FUWS components and can be expected to impact overall system performance.

Latency: This input describes the time delay at each node required to send and/or relay a message. Combined with data rate, these delays can be used to simulate the age of data informing the targeting logic.

Reliability: Sensor reliability would be used to simulate failure rates and its impact on system performance in more advanced simulation. The effect of a communication failure on the overall system will depend on the particular FUWS networked architecture. Robust architectures may be able to reroute messages around failed communication nodes. Brittle architectures may collapse if key communication lines fail.

Endurance/Power Usage: Energy is a resource consumed by every transmission. Simple simulation may assume a constant value or to time to energy exhaustion. More advanced simulations will benefit from the additional detail provided by simulating the power usage to send each message.

FUWS INPUT PARAMETERS (WEAPONS)

Number, 1 to n: The number of weapons not only establishes the number of possible engagements and overall system performance, but also can be used to inform the targeting logic, especially when attempting to focus engagements on high-value targets.

Weapon Type: The type of weapon selected will determine some of the additional fields below when MFSA is able to pull information from relevant databases. There may be multiple weapon types within a FUWS field.

Position: This describes the geographical position of a particular weapon relative to the rest of the field and is necessary for calculation of communication neighbors and engagement opportunities.

UUV Weapon Batteries: This input describes how mobile weapons are deployed in the area. The UUV may be as simple as a stationary bottom emplacement with a single weapon or as complex as a large diameter UUV patrolling with multiple torpedoes onboard.

Intercept Speed: This input describes the speed of the weapon when attempting to intercept a target. Higher search speeds reduce the time of the engagement but can also alert the target.

Search Speed: This input describes the speed of the weapon as it searches for the target in primary or secondary search modes.

Explosive Power: This describes the ability of the weapon to cause damage. The damage transferred to the vessel is a function of the explosive power of the weapon, the relative susceptibility of the particular vessel, and the range at time of detonation

Fuel: This input measures the energy or fuel on a mobile weapon and is used to determine the range

Endurance: This input is used to describe how a weapon consumes fuel at various speeds and search patterns, calculating the effective weapon range.

Reliability: Weapon reliability supports simulation of weapon failures and their impact on system performance.

Weapon Search Pattern: MFSA users operators may seek to assess the impact of different weapon primary and secondary search patterns on overall system performance.

Targeting Logic: This set of parameters describes the decision making process used to determine when to engage and where to aim a weapon. The targeting logic could also include limits on fire control solution quality, predicted weapon fuel remaining, minimum time to engagement, and other ballistic parameters.

APPENDIX D: UML ARTIFACTS

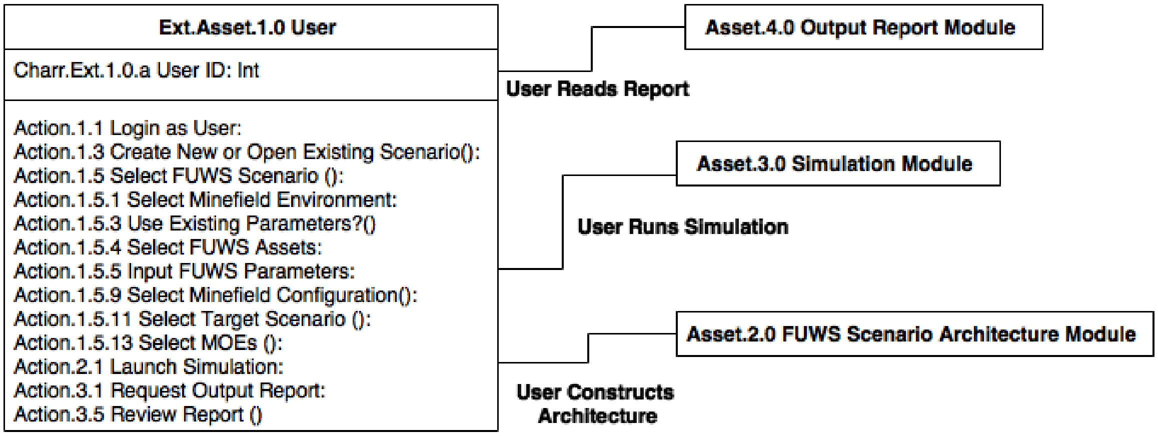


Figure 44. User Interfaces with MFSA

Figure 44 shows the interactions between the *User* class and various MFSA modules. As seen here, the *User* is responsible for constructing the architecture in the *Asset.2.0 FUWS Scenario Architecture Module*, running the simulation in the *Asset.3.0 Simulation Module* and reading and interpreting the reports provided by *Asset.4.0 Output Report Module*.

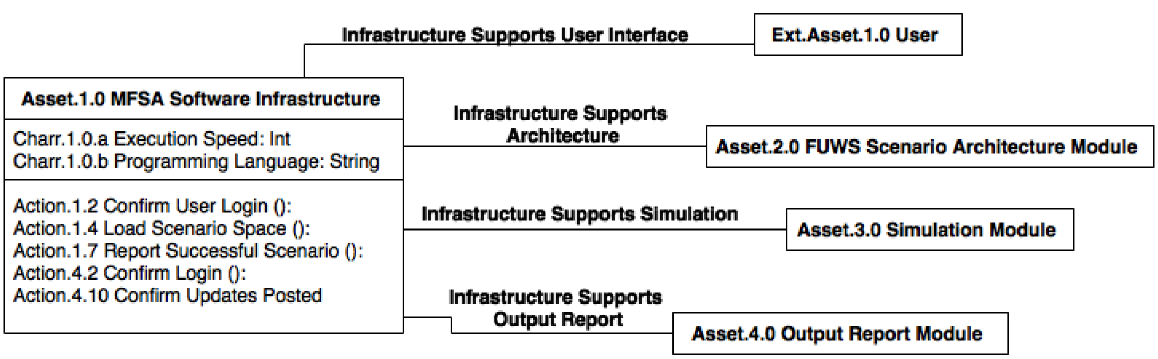


Figure 45. Software Infrastructure in User Mode

Figure 45 shows the interactions between the *MFSA Software Infrastructure* and other MFSA modules during operation by the *User*. As seen here, the *Software*

Infrastructure supports the other modules by providing the user interface environment and programming backbone required by the various MFSA modules.

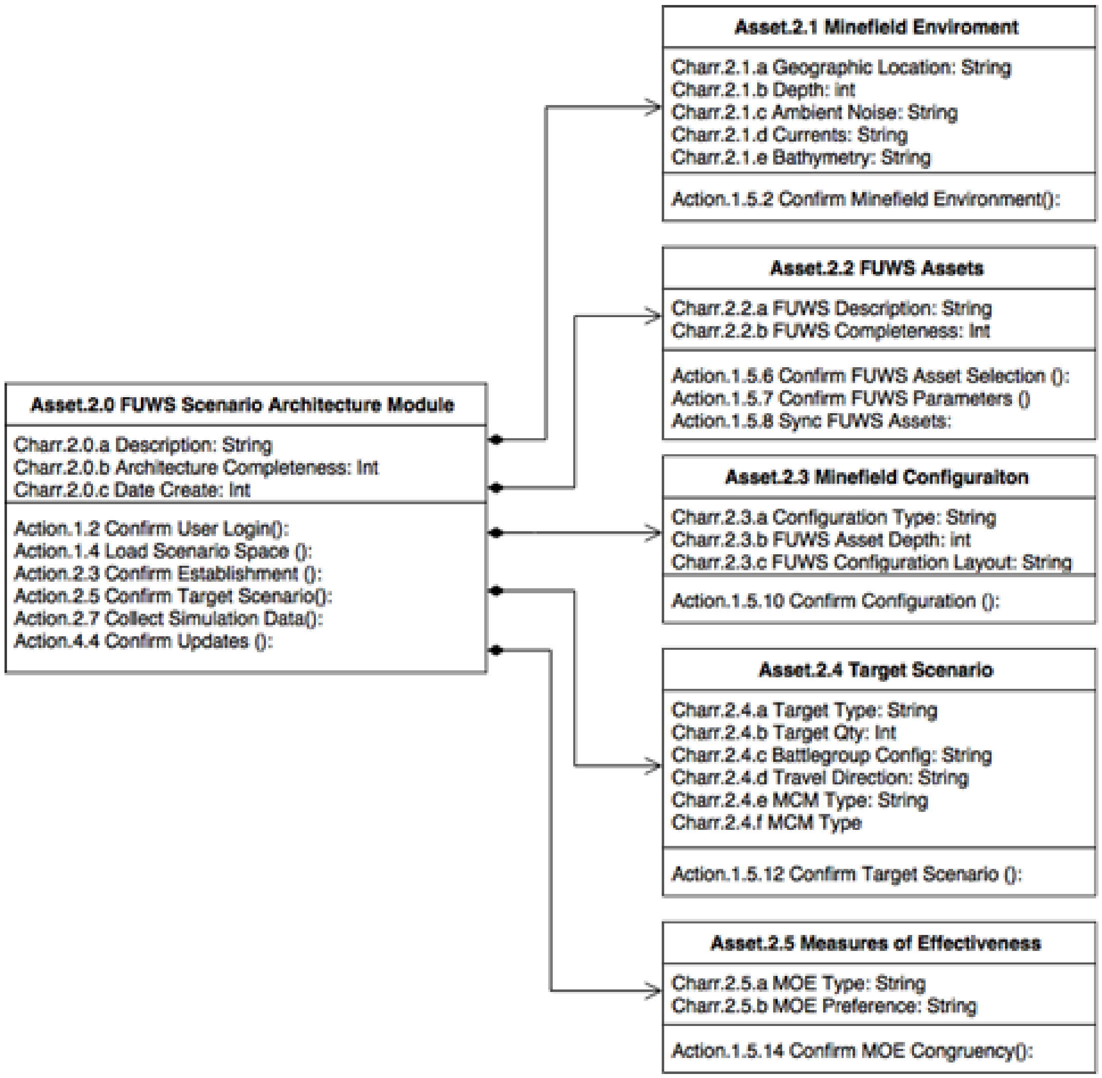


Figure 46. Decomposition of FUWS Scenario Architecture Module

Figure 46 shows the decomposition of the *FUWS Scenario Architecture Module* into component classes.

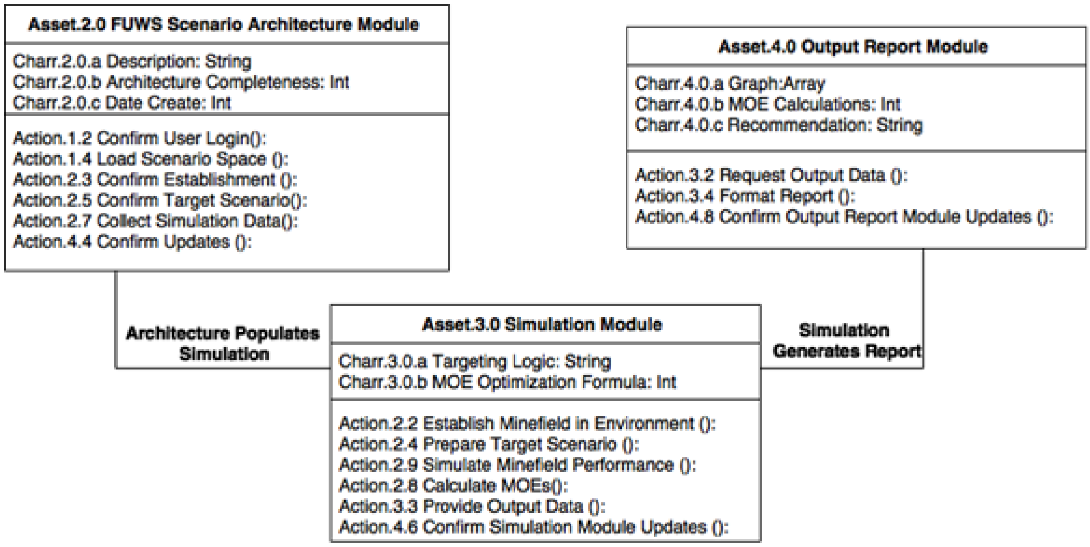


Figure 47. Simulation Module Interfaces

Figure 47 shows the interactions between the *Simulation Module* and other MFSA modules. As seen here, the *Simulation Module* inputs are provided by the *FUWS Scenario Architecture Module* and outputs are provided to the *Output Report Module.*

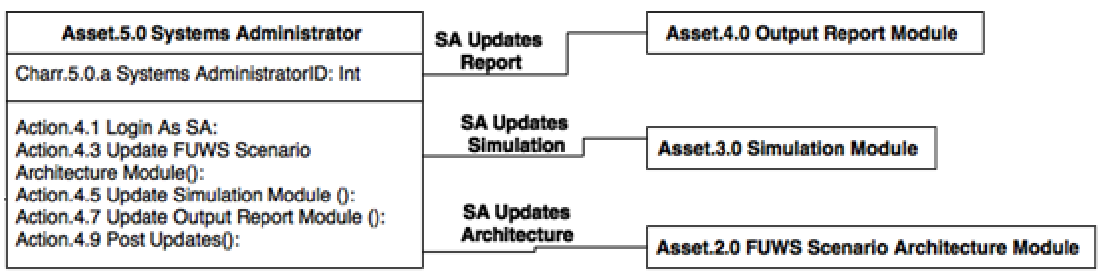


Figure 48. System Administrator Interfaces

This class diagram shows the interactions between the *System Administrator* class and various MFSA modules. As seen here, the *System Administrator* is responsible for updating and maintaining the other modules.

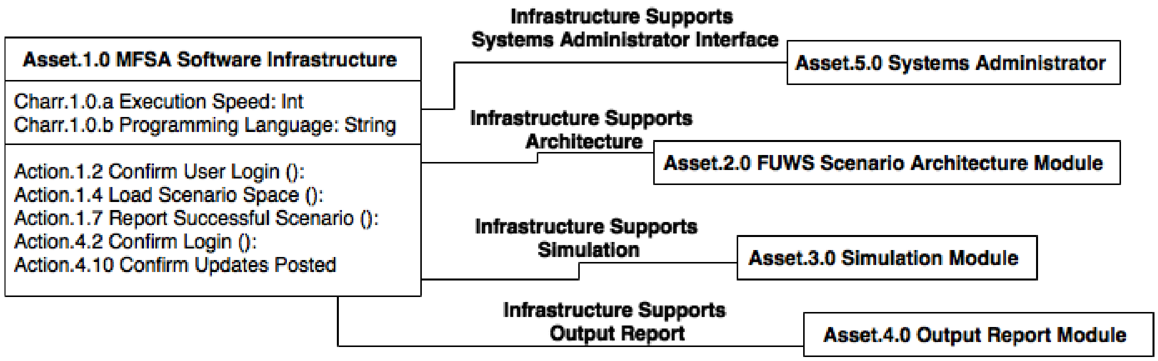


Figure 49. MFSA Software Infrastructure in Maintenance Mode

This class diagram shows the interactions between the *MFSA Software Infrastructure* and other MFSA modules during operation by the *System Administrator*. As seen here, the *Software Infrastructure* supports the other modules by providing the user interface environment required for the *System Administrator* to access the various MFSA modules.

APPENDIX E: MFSA REQUIREMENT TRACEABILITY

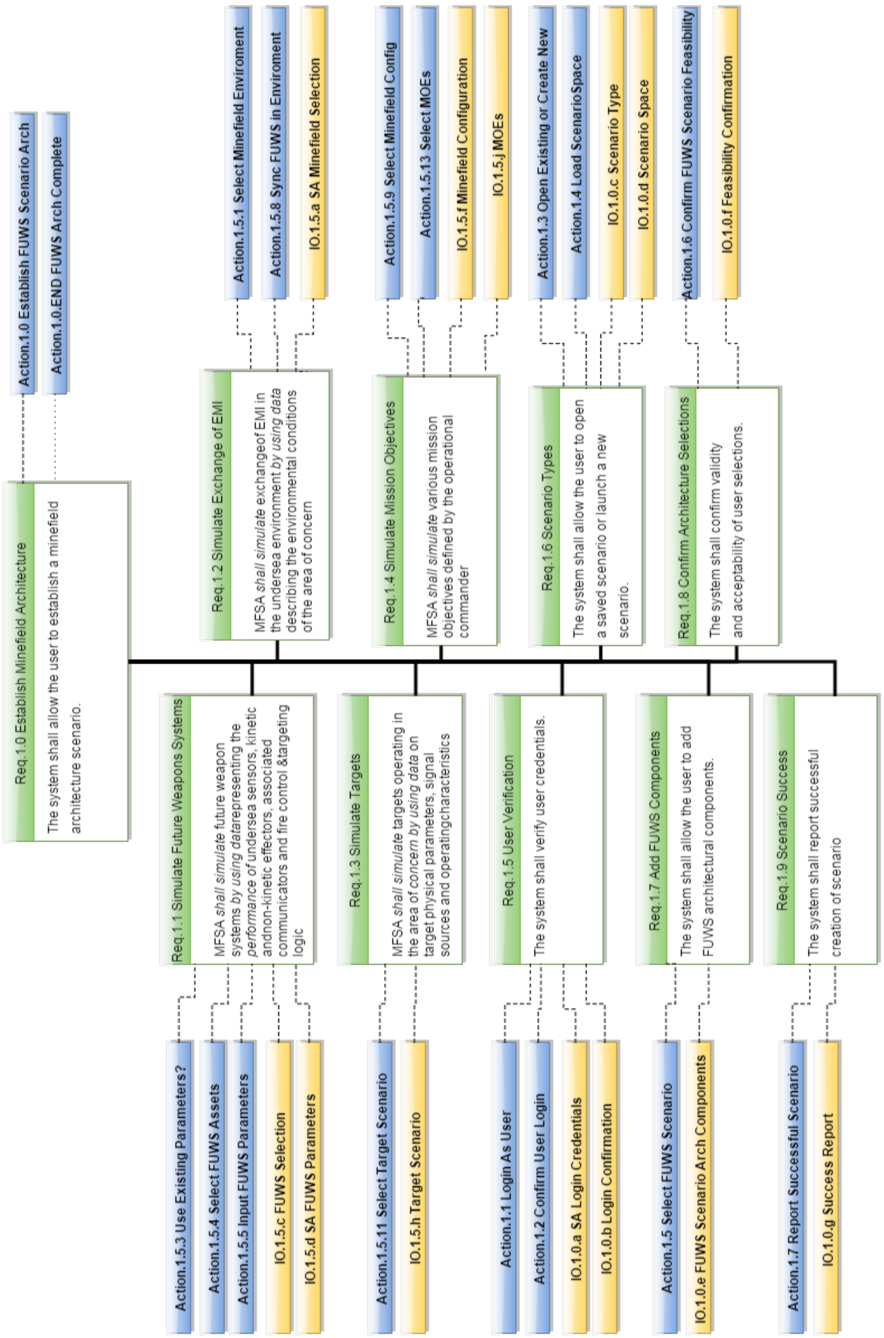


Figure 50. Establish Minefield Architecture Requirements

Figure 50 shows the decomposition of *Req.1.0 Establish Minefield Architecture* and traceability of the requirement to system actions and interfaces.

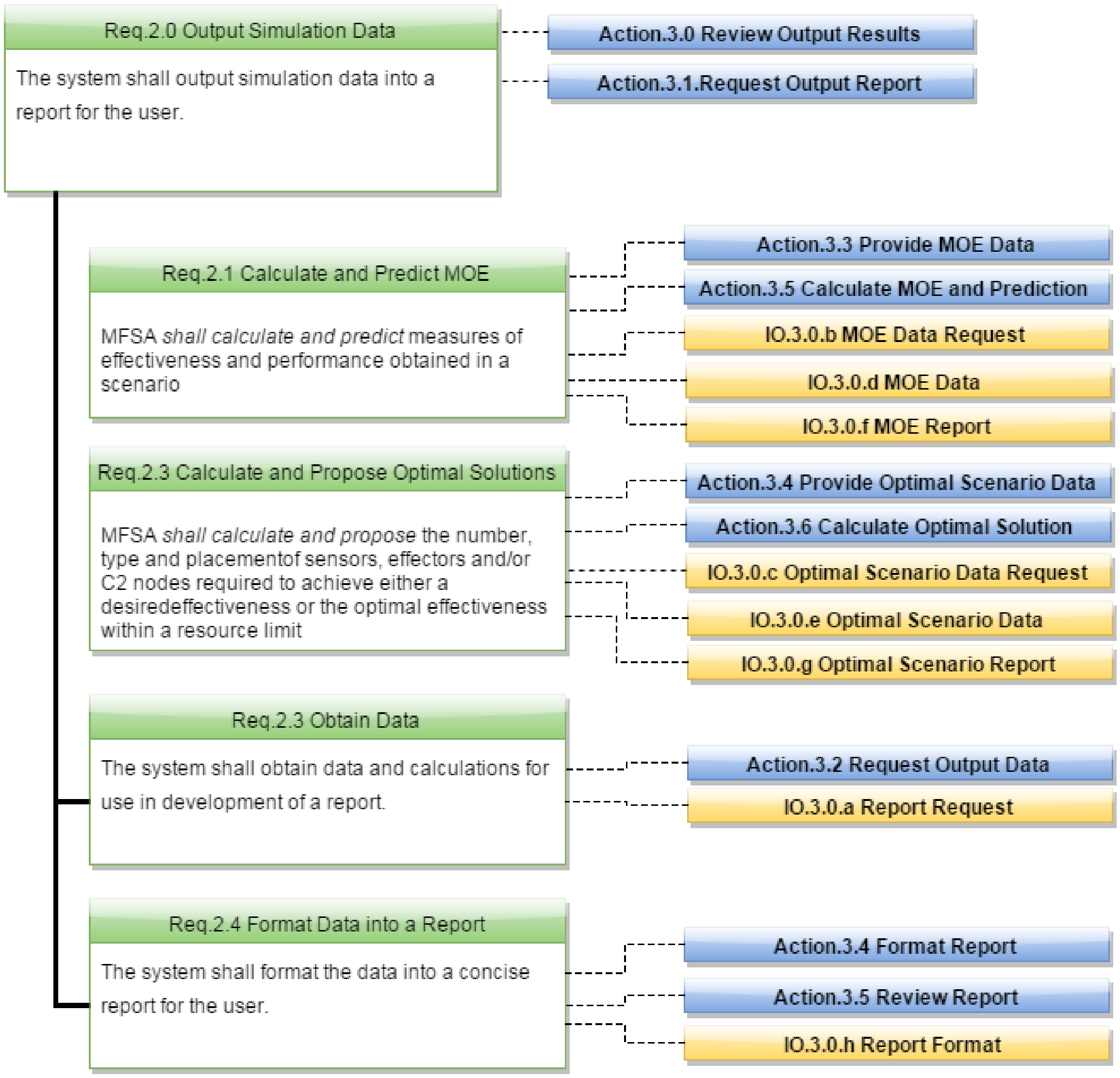


Figure 51. Output Simulation Data Requirements

Figure 51 shows the decomposition of *Req.2.0 Output Simulation Data* and traceability of the requirement to system actions and interfaces.

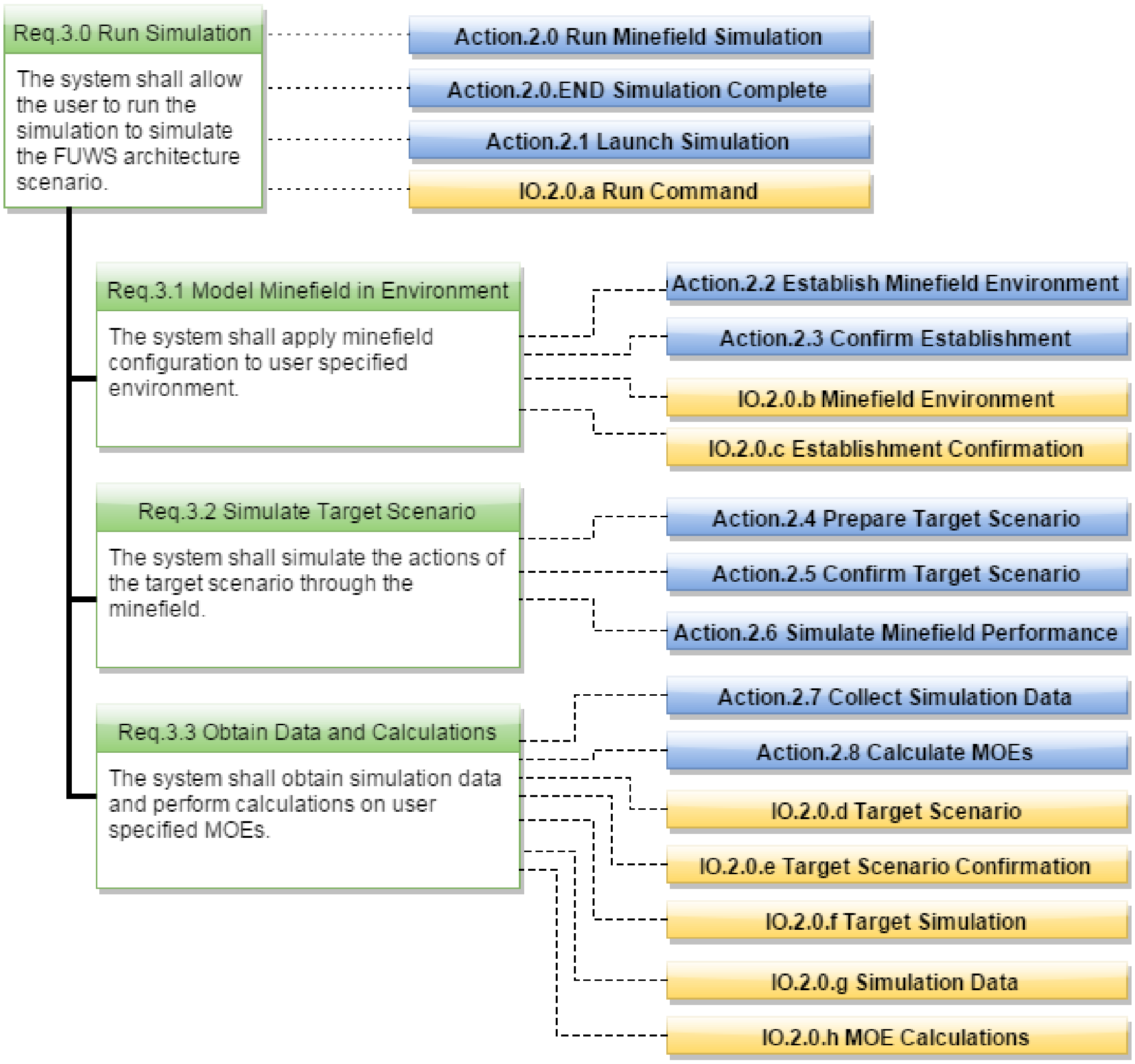


Figure 52. Run Simulation Requirements

Figure 52 shows the decomposition of *Req.3.0 Run Simulation* and traceability of the requirement to system actions and interfaces.

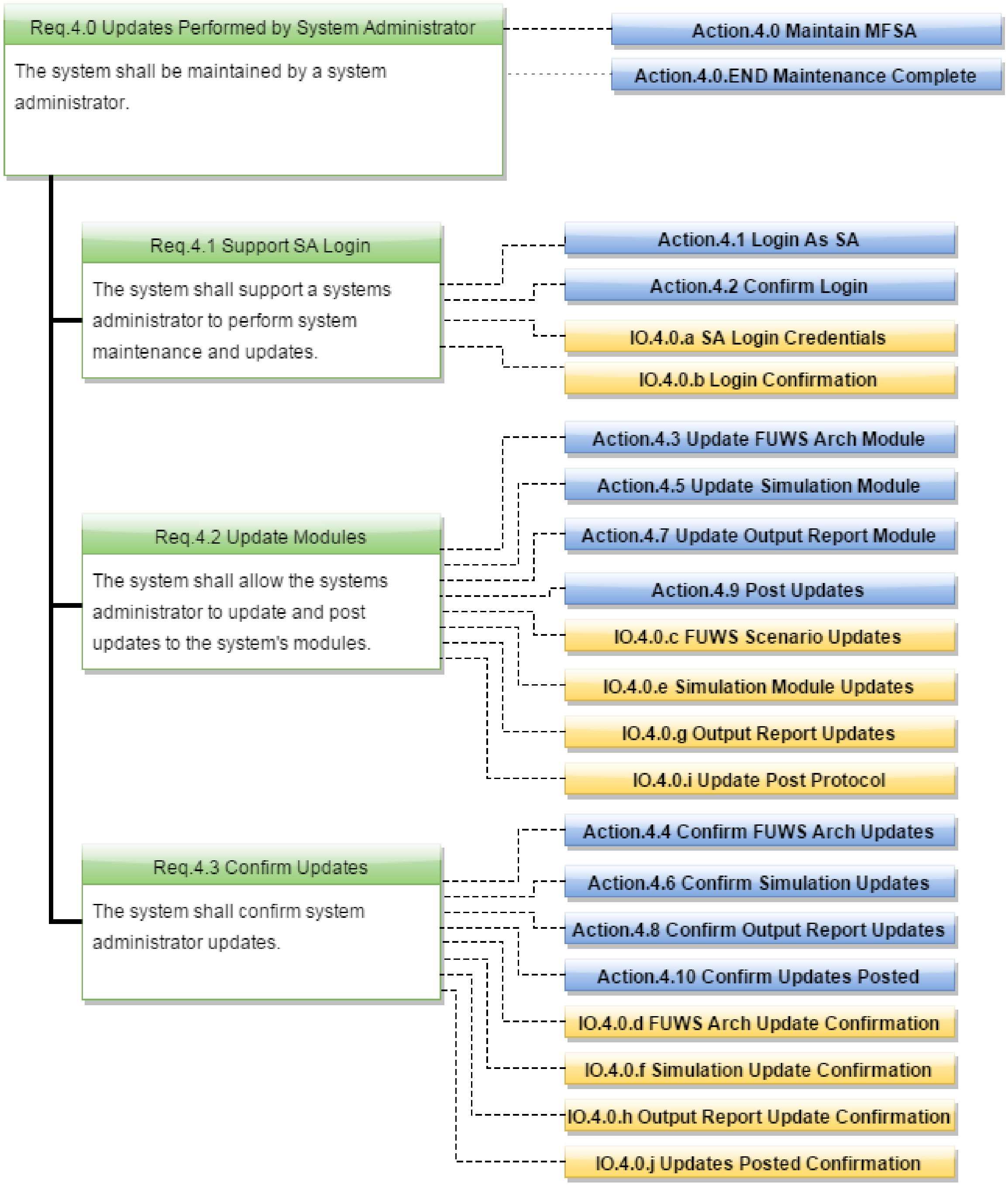


Figure 53. Update System Requirements

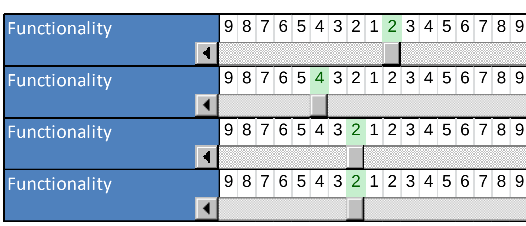
Figure 53 shows the decomposition of *Req.4.0 Update by System Administrator* and traceability of the requirement to system actions and interfaces.

APPENDIX F: PROTOTYPE TOOL SELECTION

Early in the project execution, the team conducted an analysis of available simulation environments and programming languages to support the development of the MFSA prototype. The team considered the following five capability requirements when evaluating each available simulation tool:

- Functionality. Does the tool have the features and capabilities necessary to model FUWS architecture, targeting logic, threat scenarios and MOEs? Does the tool have the desired level of complexity?
- Accessibility. Is the tool available for team use? Are there licensing concerns or data classification concerns?
- Ease of Use/ Learning Curve. How easy is it to build a model in the tool or write the code? Are there helpful tutorials or user guides?
- Display Graphical Interface. Does the tool have the desired display output to show the minefield configuration and the flow of threats through the minefield?
- Collaborative Ability. How easy is it for geographically diverse team members to work collaboratively on building the model while maintaining configuration control?

The team performed a quick pairwise comparison of these requirements to determine a relative weighting factor for each. As seen in Figure 54, accessibility and functionality were considered the most important requirements to the team. The team was confident that their collective skills and experience could compensate for lack of familiarity with the selected simulation tool (Ease of Use / Learning Curve).



Criteria		1	2	3	4	5	Weights
Functionality	1	1	1/2	4	2	2	0.2353
Accessibility	2	2	1	8	4	4	0.4706
Ease of Use Learning Curve	3	1/4	1/8	1	1/2	1/2	0.0588
Graphical Interface/ Display	4	1/2	1/4	2	1	1	0.1176
Collaborative Ability	5	1/2	1/4	2	1	1	0.1176

Figure 54. Pairwise Comparison of Modeling Tool Requirements.

The project team considered four simulation tools as backbones for development of the demonstration prototype. Requirement scores of 9 (provides all, or nearly all of the

required capability), 3 (provides some of the required capability), 1 (provides very limited) and 0 (provides no capability) were used to evaluate each system against each of the selection requirements. An overall suitability score for each tool was calculated using the sum-product of the requirement scores and requirement weighting factors from the pairwise analysis. As seen in Figure 55, Netlogo was ranked as the best tool based on its high evaluation scores on functionality and accessibility.

Relative Priority	Modeling Tools (Hows) / Team Requirement (Whats)	Microsoft Excel	Naval Simulation System (NSS)	ExtendSim	NetLogo
23.53%	Functionality	1	9	9	9
47.06%	Accessibility	9		9	9
5.88%	Ease of Use Learning Curve	9	3	3	3
11.76%	Graphical Interface/ Display	1	9	1	9
11.76%	Collaborative Ability	1		1	3
	Score	5.2353	3.3529	6.7647	7.9412
	Score%	22.5%	14.4%	29.0%	34.1%

Figure 55. Analysis of Modeling Tools

Also of note, Netlogo was the modeling tool with the highest score in collaborative ability. ExtenSim ranked second, falling slightly short of NetLogo in almost all evaluation criteria. Microsoft Excel, while widely accessible and easy to use, did not have nearly the required functionality or the desired display interfaces to make it a viable option. Finally, Naval Simulation System (NSS) promised the required functionality, but it proved to be very difficult for the team to gain access to the tool.

APPENDIX G: PROTOTYPE DEMO

The Mental Focus prototype demo can be viewed and downloaded from the Netlogo modeling commons at http://modelingcommons.org/browse/one_model/4474.

The following screenshots from the demo user interface are used to explain the interface and highlight the delivered features.

Figure 56 shows a FUWS architecture scenario. Light blue circles represent the distributed sensors with the range based network communications paths shown in grey. The light blue exes show the UUV weapon batteries. The red lines show the path histories taken by hostile ships transiting the area, allowing the user to visualize the tactic used by the threat ships.

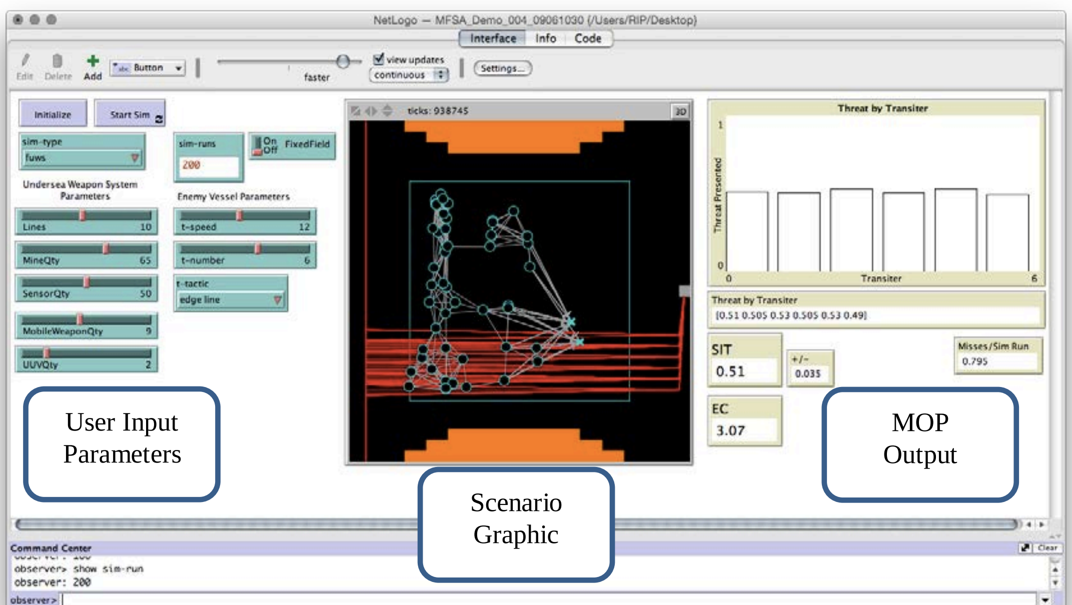


Figure 56. MFSA Demo – FUWS

Figure 57 shows a legacy architecture scenario. The interface remains the same, as do many of the graphics. However, one can see that the sensors and UUV weapon batteries are replaced by light blue circles with exes show the mines. Additionally, there are no communication paths between the mines, and thus no network.

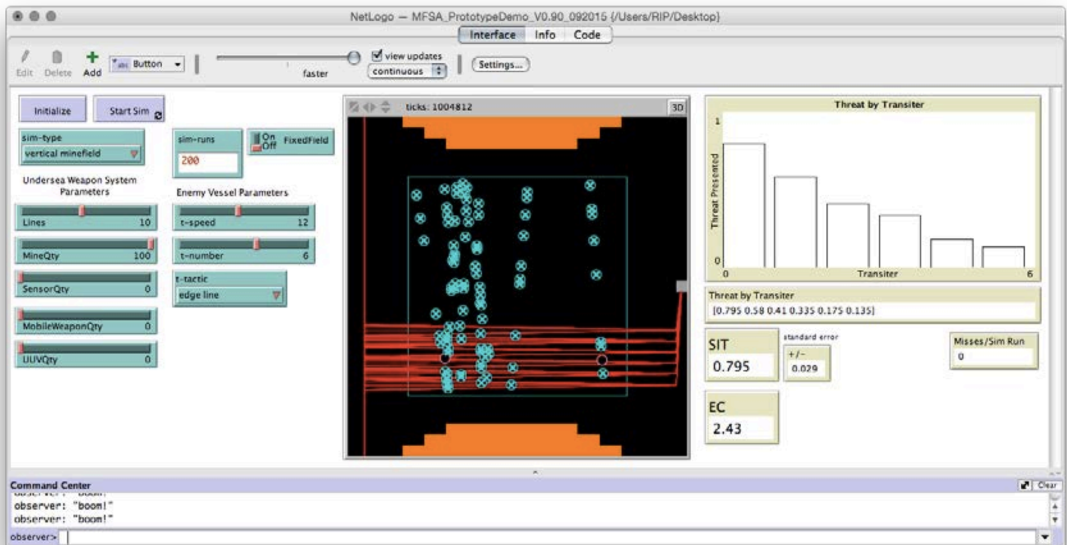


Figure 57. MFSA Demo – Legacy

APPENDIX H: PROTOTYPE SIMULATION RESULTS

This appendix provides the summary statistics, including box plots of the SIT and EC results for the Monte Carlo simulations discussed in Chapter VI. As in Chapter VI, the legacy results are highlighted in blue and the FUWS results in green to provide visual discrimination between the graphs and tables.

Figures 58 and 59 show the performance of legacy systems as a function of the number of mines deployed. For each number of mines, there are two data points, one for each number of minelines considered. Note that as the number of mines is increased, the performance (SIT or EC) increases as well.

Figures 60 and 61 similarly show the performance of FUWS architectures as a function of the number of UUV batteries to which the mobile weapons (torpedoes) are deployed. For each number of UUV batteries, there are four data points corresponding to the number of sensors and sensor lines considered. In general, for a given UUV configuration, increasing the number of sensors and the number of sensor lines tends to increase performance. Increasing the number of UUVs does not appear to appreciably impact the system performance. However, one should also note the significantly larger variation shown in the box plots for the FUWS systems. Improving the deployment algorithm to ensure UUV's are within range of the sensor network(s) and improving the target logic should reduce the variation in the FUWS system performance.

LEGACY RESULTS

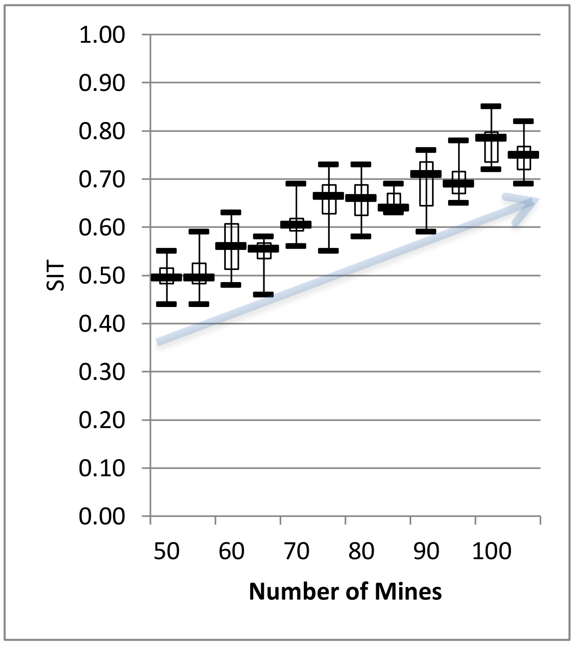


Figure 58. Boxplot: SIT versus Number of Mines

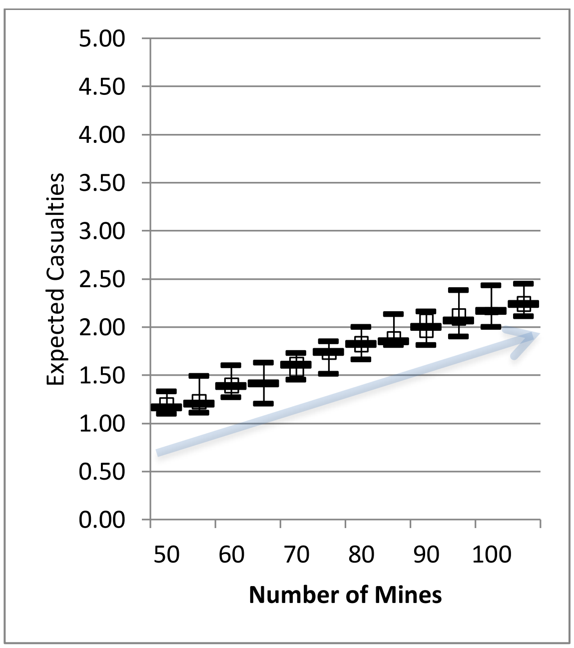


Figure 59. Boxplot: EC versus Number of Mines

Table 16. Summary Statistics 50 Mines in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.195	0.494	0.298	0.175	0.099	0.071	0.058
$\bar{x}_{trim}$	1.165	0.495	0.320	0.175	0.090	0.070	0.060
s^2	0.008	0.001	0.004	0.002	0.000	0.000	0.001
S	0.084	0.031	0.060	0.040	0.021	0.020	0.024
CV	0.070	0.063	0.200	0.229	0.209	0.278	0.421
x_{max}	1.33	0.55	0.39	0.23	0.14	0.12	0.10
$x_{75\%}$	1.26	0.52	0.33	0.21	0.11	0.08	0.07
$x_{50\%}$	1.17	0.50	0.32	0.18	0.09	0.07	0.06
$x_{25\%}$	1.14	0.48	0.27	0.14	0.09	0.06	0.04
x_{min}	1.10	0.44	0.16	0.12	0.07	0.04	0.02

Table 17. Summary Statistics 50 Mines in 10 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.231	0.502	0.304	0.182	0.101	0.078	0.064
$\bar{x}_{trim}$	1.200	0.495	0.305	0.160	0.110	0.080	0.060
s^2	0.013	0.002	0.001	0.002	0.001	0.001	0.001
S	0.110	0.042	0.035	0.044	0.029	0.023	0.025
CV	0.090	0.083	0.116	0.243	0.292	0.297	0.390
x_{max}	1.49	0.59	0.36	0.28	0.13	0.14	0.11
$x_{75\%}$	1.30	0.53	0.33	0.19	0.13	0.08	0.08
$x_{50\%}$	1.20	0.50	0.31	0.16	0.11	0.08	0.06
$x_{25\%}$	1.15	0.48	0.28	0.15	0.08	0.06	0.06
x_{min}	1.11	0.44	0.25	0.15	0.04	0.05	0.02

Table 18. Summary Statistics 60 Mines in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.401	0.559	0.348	0.200	0.136	0.092	0.066
$\bar{x}_{trim}$	1.385	0.560	0.330	0.190	0.140	0.095	0.055
s^2	0.011	0.003	0.003	0.002	0.001	0.001	0.001
S	0.098	0.055	0.054	0.040	0.035	0.034	0.030
CV	0.070	0.098	0.154	0.202	0.259	0.373	0.456
x_{max}	1.60	0.63	0.43	0.27	0.20	0.17	0.11
$x_{75\%}$	1.47	0.61	0.40	0.23	0.16	0.10	0.10
$x_{50\%}$	1.39	0.56	0.33	0.19	0.14	0.10	0.06
$x_{25\%}$	1.32	0.51	0.32	0.17	0.10	0.07	0.04
x_{min}	1.27	0.48	0.28	0.15	0.09	0.04	0.03

Table 19. Summary Statistics 60 Mines in 10 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.412	0.544	0.339	0.227	0.152	0.075	0.075
$\bar{x}_{trim}$	1.415	0.555	0.335	0.220	0.155	0.075	0.075
s^2	0.014	0.001	0.002	0.002	0.001	0.001	0.001
S	0.114	0.036	0.047	0.039	0.021	0.022	0.025
CV	0.080	0.066	0.140	0.172	0.140	0.288	0.333
x_{max}	1.63	0.58	0.42	0.33	0.18	0.11	0.11
$x_{75\%}$	1.44	0.57	0.38	0.23	0.17	0.09	0.10
$x_{50\%}$	1.42	0.56	0.34	0.22	0.16	0.08	0.08
$x_{25\%}$	1.40	0.54	0.30	0.21	0.14	0.06	0.06
x_{min}	1.20	0.46	0.27	0.17	0.10	0.04	0.03

Table 20. Summary Statistics 70 Mines in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.590	0.611	0.376	0.239	0.162	0.123	0.079
$\bar{x}_{trim}$	1.605	0.605	0.380	0.230	0.180	0.120	0.080
s^2	0.011	0.002	0.002	0.002	0.001	0.001	0.000
S	0.101	0.040	0.045	0.040	0.035	0.030	0.018
CV	0.064	0.065	0.121	0.169	0.215	0.247	0.230
x_{max}	1.73	0.69	0.43	0.30	0.20	0.17	0.11
$x_{75\%}$	1.68	0.62	0.42	0.28	0.19	0.15	0.09
$x_{50\%}$	1.61	0.61	0.38	0.23	0.18	0.12	0.08
$x_{25\%}$	1.49	0.59	0.34	0.21	0.12	0.11	0.07
x_{min}	1.45	0.56	0.29	0.17	0.12	0.06	0.04

Table 21. Summary Statistics 70 Mines in 10 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.717	0.656	0.415	0.262	0.175	0.121	0.088
$\bar{x}_{trim}$	1.740	0.665	0.425	0.270	0.185	0.115	0.070
s^2	0.010	0.002	0.004	0.001	0.001	0.001	0.001
S	0.095	0.047	0.059	0.033	0.032	0.024	0.029
CV	0.055	0.072	0.143	0.125	0.183	0.197	0.325
x_{max}	1.85	0.73	0.52	0.30	0.21	0.18	0.14
$x_{75\%}$	1.75	0.69	0.44	0.29	0.20	0.13	0.11
$x_{50\%}$	1.74	0.67	0.43	0.27	0.19	0.12	0.07
$x_{25\%}$	1.67	0.63	0.38	0.24	0.15	0.11	0.07
x_{min}	1.51	0.55	0.30	0.21	0.12	0.09	0.05

Table 22. Summary Statistics 80 Mines in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.826	0.656	0.461	0.277	0.204	0.122	0.106
$\bar{x}_{trim}$	1.820	0.660	0.460	0.275	0.215	0.120	0.110
s^2	0.013	0.002	0.003	0.001	0.003	0.001	0.000
S	0.110	0.045	0.049	0.033	0.049	0.026	0.019
CV	0.060	0.068	0.106	0.120	0.241	0.213	0.180
x_{max}	2.00	0.73	0.56	0.35	0.26	0.18	0.14
$x_{75\%}$	1.90	0.69	0.49	0.29	0.24	0.13	0.12
$x_{50\%}$	1.82	0.66	0.46	0.28	0.22	0.12	0.11
$x_{25\%}$	1.74	0.63	0.43	0.26	0.18	0.11	0.09
x_{min}	1.66	0.58	0.39	0.23	0.09	0.08	0.08

Table 23. Summary Statistics 80 Mines in 10 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	1.899	0.651	0.474	0.303	0.193	0.153	0.125
$\bar{x}_{trim}$	1.850	0.640	0.485	0.295	0.190	0.160	0.140
s^2	0.011	0.000	0.001	0.002	0.002	0.002	0.001
S	0.098	0.021	0.037	0.047	0.039	0.047	0.035
CV	0.052	0.032	0.077	0.154	0.201	0.307	0.280
x_{max}	2.13	0.69	0.51	0.39	0.25	0.23	0.16
$x_{75\%}$	1.95	0.67	0.51	0.33	0.23	0.18	0.15
$x_{50\%}$	1.85	0.64	0.49	0.30	0.19	0.16	0.14
$x_{25\%}$	1.83	0.63	0.45	0.26	0.16	0.14	0.10
x_{min}	1.81	0.63	0.40	0.25	0.14	0.07	0.06

Table 24. Summary Statistics 90 Mines in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	2.004	0.691	0.497	0.339	0.219	0.143	0.115
$\bar{x}_{trim}$	2.000	0.710	0.500	0.340	0.220	0.140	0.115
s^2	0.018	0.004	0.002	0.002	0.001	0.001	0.001
S	0.126	0.057	0.043	0.041	0.036	0.032	0.028
CV	0.063	0.082	0.086	0.120	0.166	0.223	0.247
x_{max}	2.16	0.76	0.55	0.39	0.26	0.19	0.16
$x_{75\%}$	2.13	0.74	0.54	0.38	0.26	0.17	0.13
$x_{50\%}$	2.00	0.71	0.50	0.34	0.22	0.14	0.12
$x_{25\%}$	1.90	0.65	0.47	0.33	0.19	0.12	0.09
x_{min}	1.81	0.59	0.41	0.26	0.16	0.09	0.08

Table 25. Summary Statistics 90 Mines in 10 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	2.111	0.699	0.527	0.361	0.228	0.174	0.122
$\bar{x}_{trim}$	2.065	0.690	0.530	0.355	0.240	0.165	0.125
s^2	0.023	0.002	0.002	0.003	0.003	0.001	0.000
S	0.145	0.041	0.040	0.048	0.049	0.026	0.017
CV	0.069	0.058	0.076	0.132	0.214	0.150	0.136
x_{max}	2.38	0.78	0.58	0.46	0.31	0.23	0.15
$x_{75\%}$	2.19	0.72	0.56	0.40	0.26	0.18	0.13
$x_{50\%}$	2.07	0.69	0.53	0.36	0.24	0.17	0.13
$x_{25\%}$	2.02	0.67	0.51	0.32	0.18	0.16	0.11
x_{min}	1.90	0.65	0.45	0.30	0.15	0.14	0.10

Table 26. Summary Statistics 100 Mines in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
N	10	10	10	10	10	10	10
$\bar{x}$	2.188	0.776	0.525	0.365	0.242	0.150	0.130
$\bar{x}_{trim}$	2.165	0.785	0.520	0.370	0.260	0.145	0.140
s^2	0.014	0.002	0.006	0.001	0.002	0.001	0.001
S	0.114	0.041	0.075	0.034	0.037	0.035	0.028
CV	0.052	0.052	0.142	0.093	0.152	0.237	0.212
x_{max}	2.43	0.85	0.64	0.42	0.28	0.21	0.16
$x_{75\%}$	2.20	0.80	0.58	0.39	0.27	0.18	0.16
$x_{50\%}$	2.17	0.79	0.52	0.37	0.26	0.15	0.14
$x_{25\%}$	2.13	0.74	0.48	0.35	0.22	0.12	0.11
x_{min}	2.00	0.72	0.41	0.29	0.17	0.11	0.08

Table 27. Summary Statistics 100 Mines in 10 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	10	10	10	10	10	10	10
$\bar{x}$	2.250	0.749	0.559	0.372	0.258	0.175	0.137
$\bar{x}_{trim}$	2.240	0.750	0.545	0.360	0.260	0.185	0.140
s^2	0.011	0.002	0.002	0.002	0.002	0.001	0.002
S	0.099	0.041	0.043	0.039	0.039	0.035	0.037
CV	0.044	0.055	0.077	0.104	0.150	0.202	0.273
x_{max}	2.45	0.82	0.64	0.45	0.32	0.23	0.20
$x_{75\%}$	2.32	0.77	0.59	0.39	0.29	0.19	0.15
$x_{50\%}$	2.24	0.75	0.55	0.36	0.26	0.19	0.14
$x_{25\%}$	2.17	0.72	0.54	0.35	0.23	0.15	0.11
x_{min}	2.11	0.69	0.49	0.31	0.20	0.11	0.08

FUWS RESULTS

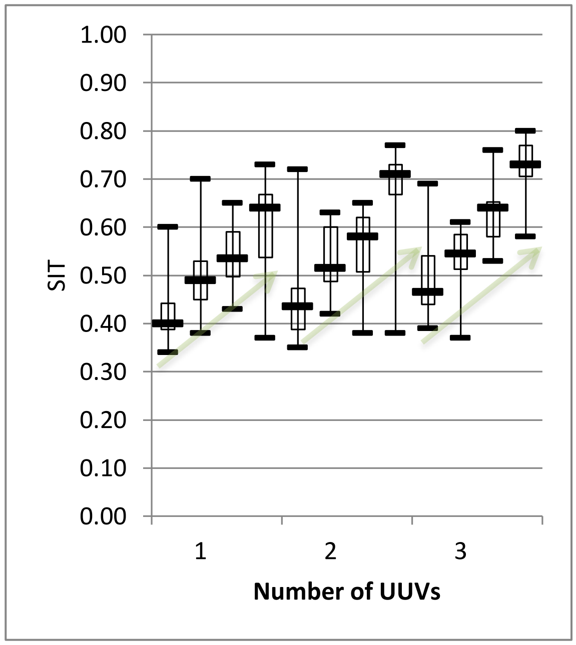


Figure 60. Boxplot: SIT versus Number of Mines

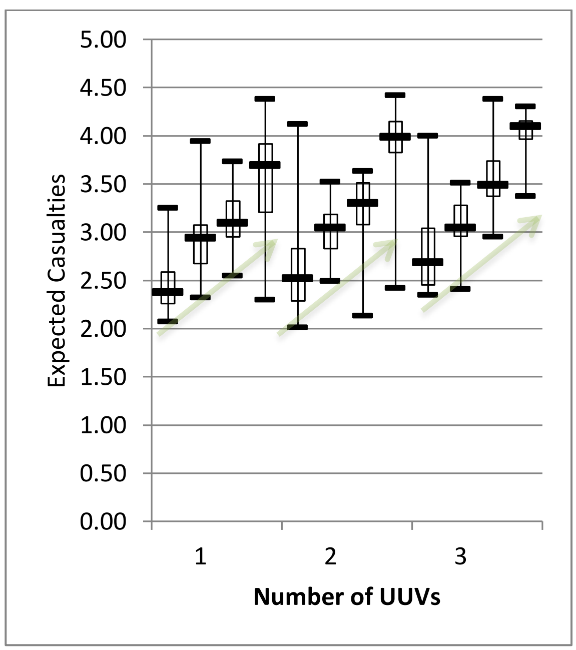


Figure 61. Boxplot: EC versus Number of Mines

Table 28. Summary Statistics 1 UUV and 50 Sensors in 2 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	2.465	0.421	0.421	0.414	0.415	0.419	0.377
$\bar{x}_{trim}$	2.370	0.403	0.415	0.400	0.405	0.410	0.360
s^2	0.100	0.005	0.002	0.003	0.003	0.003	0.003
S	0.308	0.067	0.057	0.056	0.056	0.050	0.057
CV	0.125	0.159	0.135	0.134	0.134	0.118	0.151
x_{max}	3.25	0.60	0.56	0.54	0.57	0.55	0.50
$x_{75\%}$	2.59	0.44	0.43	0.45	0.44	0.42	0.41
$x_{50\%}$	2.38	0.40	0.42	0.40	0.41	0.41	0.36
$x_{25\%}$	2.26	0.39	0.39	0.39	0.39	0.38	0.33
x_{min}	2.07	0.34	0.33	0.31	0.33	0.35	0.30

Table 29. Summary Statistics 1 UUV and 50 Sensors in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	2.930	0.494	0.504	0.486	0.493	0.494	0.459
$\bar{x}_{trim}$	2.940	0.493	0.518	0.485	0.485	0.490	0.445
s^2	0.136	0.005	0.003	0.005	0.004	0.005	0.003
S	0.360	0.071	0.067	0.066	0.061	0.071	0.056
CV	0.123	0.143	0.133	0.135	0.124	0.143	0.123
x_{max}	3.94	0.70	0.68	0.64	0.65	0.68	0.59
$x_{75\%}$	3.07	0.53	0.53	0.53	0.53	0.54	0.48
$x_{50\%}$	2.94	0.49	0.52	0.49	0.49	0.49	0.45
$x_{25\%}$	2.68	0.45	0.46	0.45	0.45	0.44	0.42
x_{min}	2.32	0.38	0.38	0.38	0.41	0.36	0.39

Table 30. Summary Statistics 1 UUV and 100 Sensors in 2 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	3.120	0.535	0.526	0.534	0.526	0.524	0.476
$\bar{x}_{trim}$	3.105	0.533	0.528	0.530	0.528	0.528	0.473
s^2	0.081	0.003	0.003	0.003	0.003	0.002	0.004
S	0.278	0.055	0.040	0.057	0.050	0.044	0.065
CV	0.089	0.103	0.075	0.107	0.094	0.083	0.137
x_{max}	3.73	0.65	0.63	0.64	0.62	0.60	0.62
$x_{75\%}$	3.32	0.59	0.54	0.58	0.55	0.55	0.51
$x_{50\%}$	3.10	0.54	0.53	0.53	0.53	0.53	0.48
$x_{25\%}$	2.95	0.50	0.51	0.51	0.49	0.51	0.44
x_{min}	2.55	0.43	0.45	0.42	0.43	0.40	0.37

Table 31. Summary Statistics 1 UUV and 100 Sensors in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	3.507	0.598	0.604	0.596	0.585	0.577	0.547
$\bar{x}_{trim}$	3.693	0.633	0.630	0.620	0.613	0.588	0.583
s^2	0.348	0.011	0.004	0.010	0.010	0.009	0.011
S	0.575	0.102	0.105	0.095	0.100	0.090	0.102
CV	0.164	0.171	0.174	0.159	0.170	0.157	0.186
x_{max}	4.38	0.73	0.75	0.78	0.77	0.71	0.68
$x_{75\%}$	3.92	0.67	0.67	0.66	0.65	0.65	0.62
$x_{50\%}$	3.70	0.64	0.64	0.62	0.61	0.59	0.59
$x_{25\%}$	3.21	0.54	0.58	0.55	0.52	0.52	0.51
x_{min}	2.30	0.37	0.38	0.42	0.38	0.37	0.34

Table 32. Summary Statistics 2 UUV and 50 Sensors in 2 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
N	20	20	20	20	20	20	20
$\bar{x}$	2.644	0.456	0.447	0.469	0.440	0.445	0.388
$\bar{x}_{trim}$	2.520	0.438	0.428	0.453	0.423	0.428	0.383
s^2	0.301	0.010	0.002	0.008	0.010	0.009	0.008
S	0.534	0.097	0.098	0.089	0.098	0.090	0.088
CV	0.202	0.213	0.220	0.189	0.224	0.202	0.226
x_{max}	4.12	0.72	0.70	0.70	0.68	0.70	0.62
$x_{75\%}$	2.83	0.47	0.48	0.49	0.47	0.49	0.41
$x_{50\%}$	2.52	0.44	0.43	0.45	0.42	0.43	0.39
$x_{25\%}$	2.29	0.39	0.38	0.42	0.38	0.37	0.34
x_{min}	2.01	0.35	0.30	0.36	0.29	0.34	0.25

Table 33. Summary Statistics 2 UUV and 50 Sensors in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
N	20	20	20	20	20	20	20
$\bar{x}$	3.025	0.530	0.514	0.517	0.508	0.510	0.446
$\bar{x}_{trim}$	3.028	0.520	0.510	0.525	0.510	0.500	0.450
s^2	0.064	0.005	0.003	0.004	0.002	0.003	0.002
S	0.246	0.067	0.056	0.063	0.047	0.052	0.042
CV	0.081	0.126	0.109	0.122	0.092	0.102	0.094
x_{max}	3.52	0.63	0.64	0.62	0.60	0.61	0.53
$x_{75\%}$	3.18	0.60	0.55	0.57	0.54	0.54	0.47
$x_{50\%}$	3.05	0.52	0.51	0.52	0.51	0.50	0.45
$x_{25\%}$	2.83	0.49	0.48	0.47	0.48	0.47	0.43
x_{min}	2.49	0.42	0.41	0.39	0.41	0.43	0.37

Table 34. Summary Statistics 2 UUV and 100 Sensors in 2 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	3.264	0.562	0.569	0.576	0.558	0.529	0.472
$\bar{x}_{trim}$	3.318	0.583	0.578	0.590	0.553	0.535	0.485
s^2	0.120	0.005	0.003	0.003	0.003	0.003	0.005
S	0.338	0.068	0.073	0.055	0.057	0.055	0.066
CV	0.103	0.121	0.129	0.096	0.102	0.104	0.140
x_{max}	3.63	0.65	0.68	0.64	0.66	0.62	0.56
$x_{75\%}$	3.51	0.62	0.60	0.61	0.59	0.56	0.52
$x_{50\%}$	3.30	0.58	0.58	0.59	0.55	0.54	0.49
$x_{25\%}$	3.08	0.51	0.55	0.56	0.53	0.51	0.43
x_{min}	2.13	0.38	0.33	0.40	0.40	0.34	0.28

Table 35. Summary Statistics 2 UUV and 100 Sensors in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	3.818	0.669	0.683	0.672	0.642	0.612	0.541
$\bar{x}_{trim}$	3.980	0.710	0.708	0.698	0.673	0.625	0.563
s^2	0.316	0.013	0.005	0.011	0.010	0.006	0.008
S	0.548	0.109	0.103	0.100	0.096	0.077	0.086
CV	0.144	0.164	0.151	0.150	0.149	0.126	0.159
x_{max}	4.42	0.77	0.81	0.77	0.78	0.70	0.67
$x_{75\%}$	4.15	0.73	0.75	0.73	0.71	0.67	0.59
$x_{50\%}$	3.99	0.71	0.71	0.70	0.67	0.63	0.56
$x_{25\%}$	3.83	0.67	0.65	0.67	0.60	0.60	0.53
x_{min}	2.42	0.38	0.45	0.40	0.42	0.41	0.31

Table 36. Summary Statistics 3 UUV and 50 Sensors in 2 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	2.819	0.496	0.501	0.490	0.481	0.457	0.395
$\bar{x}_{trim}$	2.690	0.465	0.483	0.465	0.478	0.450	0.385
s^2	0.212	0.008	0.002	0.008	0.006	0.005	0.006
S	0.449	0.085	0.089	0.086	0.077	0.066	0.075
CV	0.159	0.172	0.178	0.176	0.161	0.144	0.189
x_{max}	4.00	0.69	0.77	0.70	0.68	0.59	0.57
$x_{75\%}$	3.04	0.54	0.54	0.53	0.51	0.51	0.44
$x_{50\%}$	2.69	0.47	0.49	0.46	0.48	0.45	0.38
$x_{25\%}$	2.46	0.44	0.43	0.42	0.42	0.43	0.34
x_{min}	2.35	0.39	0.38	0.37	0.36	0.33	0.29

Table 37. Summary Statistics 3 UUV and 50 Sensors in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	3.072	0.537	0.521	0.536	0.536	0.498	0.445
$\bar{x}_{trim}$	3.045	0.545	0.523	0.533	0.543	0.495	0.445
s^2	0.082	0.004	0.003	0.004	0.003	0.004	0.003
S	0.279	0.060	0.057	0.059	0.056	0.058	0.055
CV	0.091	0.112	0.110	0.110	0.104	0.117	0.125
x_{max}	3.51	0.61	0.61	0.63	0.63	0.62	0.54
$x_{75\%}$	3.28	0.59	0.56	0.58	0.57	0.52	0.49
$x_{50\%}$	3.05	0.55	0.52	0.54	0.54	0.50	0.45
$x_{25\%}$	2.96	0.51	0.49	0.49	0.51	0.46	0.42
x_{min}	2.41	0.37	0.41	0.43	0.41	0.38	0.32

Table 38. Summary Statistics 3 UUV and 100 Sensors in 2 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	3.546	0.630	0.616	0.629	0.614	0.574	0.485
$\bar{x}_{trim}$	3.513	0.640	0.613	0.635	0.605	0.568	0.488
s^2	0.118	0.004	0.004	0.006	0.005	0.004	0.004
S	0.334	0.060	0.063	0.073	0.068	0.059	0.062
CV	0.094	0.096	0.102	0.116	0.111	0.103	0.128
x_{max}	4.38	0.76	0.77	0.79	0.79	0.70	0.61
$x_{75\%}$	3.74	0.65	0.64	0.67	0.65	0.61	0.52
$x_{50\%}$	3.49	0.64	0.61	0.63	0.61	0.57	0.49
$x_{25\%}$	3.37	0.58	0.58	0.57	0.57	0.55	0.46
x_{min}	2.95	0.53	0.53	0.51	0.51	0.47	0.33

Table 39. Summary Statistics 3 UUV and 100 Sensors in 5 Lines

	EC	SIT	T_2	T_3	T_4	T_5	T_6
n	20	20	20	20	20	20	20
$\bar{x}$	4.022	0.729	0.711	0.712	0.709	0.641	0.522
$\bar{x}_{trim}$	4.093	0.733	0.710	0.715	0.728	0.645	0.535
s^2	0.051	0.003	0.005	0.002	0.003	0.001	0.002
S	0.221	0.051	0.052	0.046	0.055	0.038	0.044
CV	0.055	0.070	0.073	0.065	0.078	0.059	0.085
x_{max}	4.30	0.80	0.82	0.79	0.77	0.70	0.60
$x_{75\%}$	4.15	0.77	0.75	0.74	0.75	0.67	0.54
$x_{50\%}$	4.10	0.73	0.71	0.72	0.73	0.65	0.54
$x_{25\%}$	3.97	0.71	0.67	0.68	0.67	0.62	0.51
x_{min}	3.37	0.58	0.63	0.60	0.58	0.55	0.41

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX I: USER INTERFACE DEMO

To support MFSA architectural design and discovery of user interface requirements, the Mental Focus team created the following graphics to support visualizing the MFSA graphic user interfaces (GUI) in various user scenarios. To enhance user acceptance, the team patterned the GUI design on typical Department of Defense software products, including the Global Command and Control System – Maritime (GCCS-M) currently used as the backbone for minefield planning tools such as the Mine Warfare Decision Aide Library (MEDAL).

Figure 62 shows the MFSA concept GUI during the creation and setup of a simulation scenario for analysis by an operational planner.

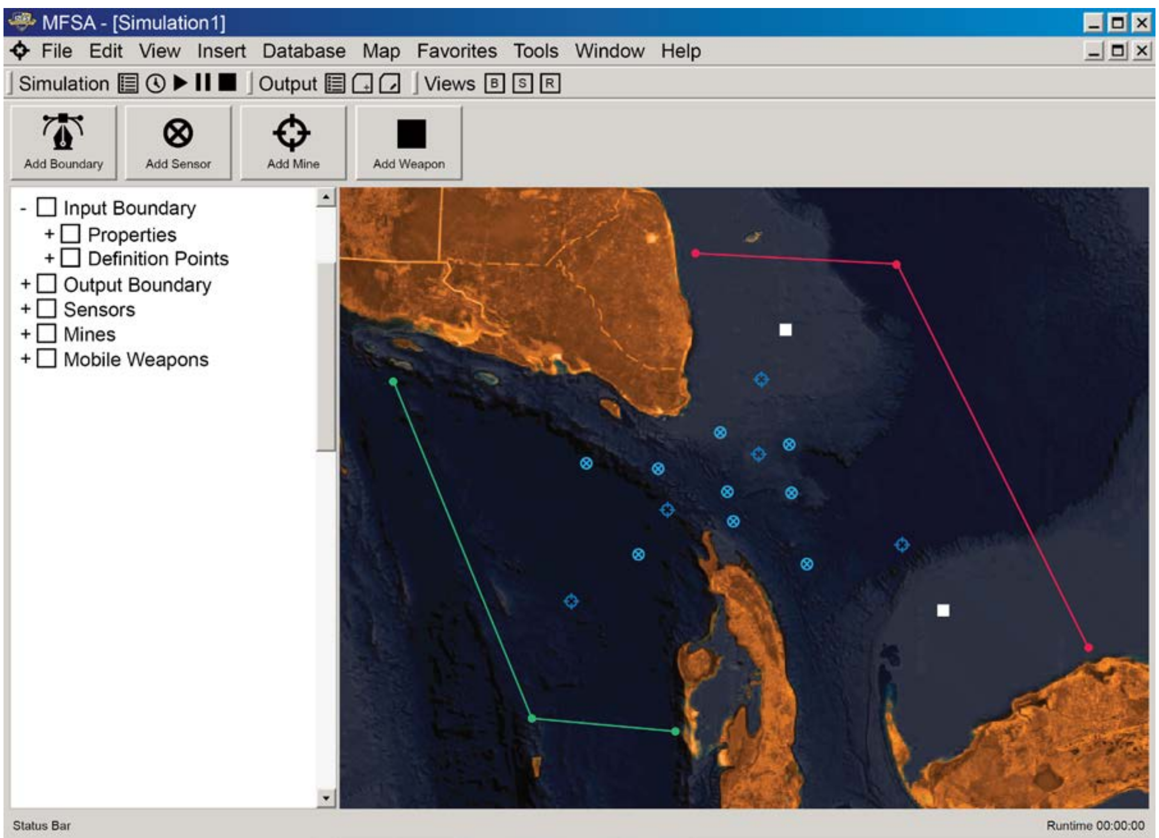


Figure 62. Simulation Setup

Across the top of the window is the user navigation and control section of the GUI; including features common to most desktop applications. Below this is a toolbar where the user can control the simulation, and toggle user modes and views. Along the left is a scenario directory, which presents the model components in a tabular form. This directory allows the user to quickly view and edit components, including the statistical properties driving the simulation. The visualization window shows the geographic layout of system components, including in this case a hybrid system of mines, sensors and weapons, as well as the boundaries of the counter-mobility area and geographic features.

The team envisions that, upon opening a new simulation activity, the user would select the geographic location, loading in all environmental and topographic properties for the area of interest. Figure 60 shows a navigational straight with topographic information displayed as a textured over-lay on the water (black) and land (orange). Using a pen tool, the user could define input and output boundaries as vector, including multiple points as needed for the required fidelity. The green boundary in Figure 60 represents the input source for threats, where threats originate, and the red boundary provides the target goal for navigational success, representing a failure of the undersea weapon system.

For adding new assets to the system, the user can select one of the "add" buttons across the top navigation and place it visually on the map in the visualization window. Alternatively, the user can add components using the scenario directory and specify the placement in the asset's properties using an input or randomized location.

Figure 63 shows the MFSA concept GUI during a visualized simulation run. It shows a hostile ship, a red dot, transiting from the input boundary along a navigable path into the straight. The target's path is traced with a line when visualizing the simulation to support understanding the target's selected path and it's impact on system performance. At each step in the simulation, MFSA determines the status of detecting sensors. Figure 63 shows a white ring around a detecting sensor, with a radius equal to the range of the threat from the sensor. This allows the user to visualize the likely detection range of the sensor had the threat taken an alternative path, and confirm the adequacy of sensor coverage.

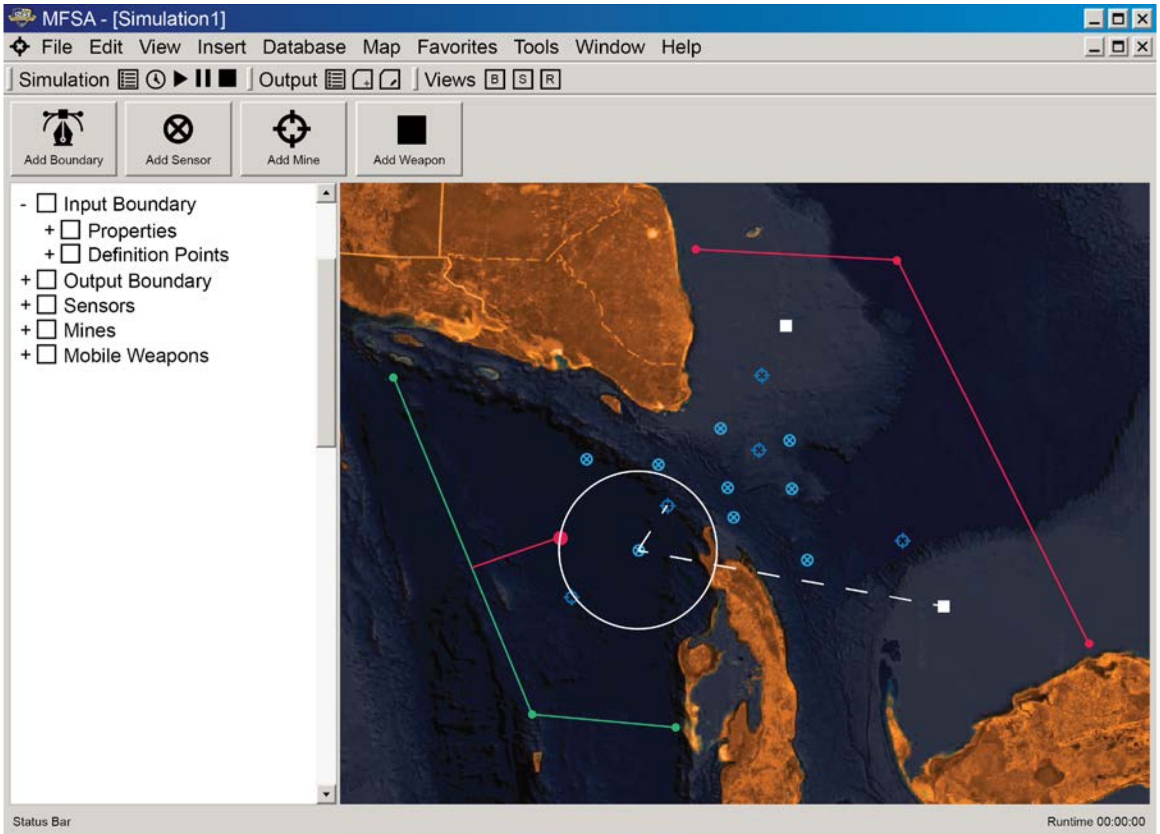


Figure 63. Simulation Run

MFSA should also support visualization of the communications transfer between FUWS components. Figure 63 shows a sensor reporting (dashed white line) to a mobile weapon asset battery the detection of the hostile warship. As additional sensors are triggered and the system launches an intercept weapon, MFSA would graphically display these milestones. As an appropriate weapon is identified and launched toward a projected intercept point, the path of the weapon would be displayed as well. The purpose of visualizing of each step in this process is to provide the user an understanding of the model response, allowing the user to understand the value provided by individual components based on location and performance properties. Alternatively, the user could disable visualizations when conducting large numbers of Monte Carlo simulations to support statistical analysis.

Figure 64 shows a potential visualization of MFSA output data. While the reporting features of MFSA could provide a catalog of the simulation record including

milestone events such as the change in state of assets in the field of operation, the selected output performance parameters, such as SIT and EC, would need to be readily available to the user. The team also envisioned the capability to provide a gradient map, similar to what may be seen in computational fluid dynamics or finite element analysis programs, that would show the system performance across the area. MFSA could use color-coding to indicate areas where performance achieved a specified level of performance and areas where the system assumed risk. In Figure 64, green regions signify areas with the lowest risk of failure against the threat, while yellow and red regions indicate areas where the threat can operate with relative safety. In other words, green regions are well defended, while red are less so. This allows the user to identify areas that may require additional sensors or weapon coverage and supports a more sophisticated system deployment

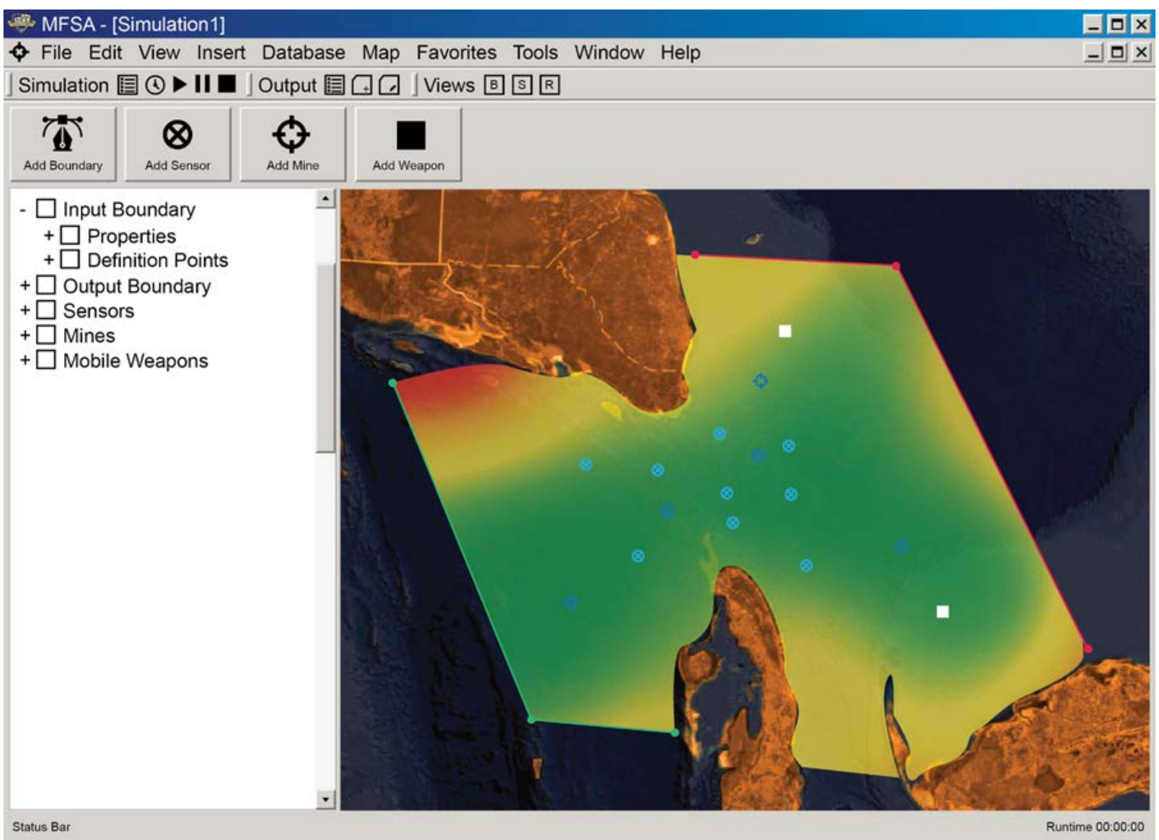


Figure 64. Simulation Output

LIST OF REFERENCES

Akyildiz, Ian F., and Ismail H. Kasimoglu. 2004. "Wireless Sensor and Actor Networks: Research Challenges." *Ad Hoc Networks* 2 (4): 351–367. doi:10.1016/j.adhoc.2004.04.003.

Axelrod, Robert and Leigh Tesfatsion. 2015. "On-Line Guide for Newcomers to Agent-Based Modeling in the Social Sciences." Iowa State University. http://www2.econ.iastate.edu/tesfatsi/abmread.htm

Bard, William. 2013. "Naval Minefield Modeling and Simulation: An Examination of General Analytical Minefield Evaluation Tool (GAMET) and Other Minefield Models." Masters thesis, Naval Postgraduate School.

Belton, Brian. 2011. "General Analytical Minefield Evaluation Tool." NDIA 2011 Joint Undersea Warfare Technology Spring Conference.

———. 2015. "General Analytical Minefield Evaluation Tool." San Diego, CA: SSC Pacific.

———. 2015. "General Analytical Minefield Evaluation Tool (GAMET) User's Guide." Version 3.3.3. Panama City, FL: Naval Surface Warfare Center.

Blanchard, Benjamin S., and W. J. Fabrycky. 2011. *Systems Engineering and Analysis*. 5th ed. Boston: Prentice Hall.

Budgen, David. 1994. *Software Design*. Boston, MA: Addison-Wesley.

Buede, Dennis M. 2009. *The Engineering Design of Systems: Models and Method*s. 2nd ed. New York: Wiley.

Committee for Mine Warfare Assessment. 2001. *Naval Mine Warfare: Operational and Technical Challenges for Naval Forces*. Washington, DC: National Academy Press. http://www.nap.edu/catalog/10176/naval-mine-warfare-operational-and-technical-challenges-for-naval-forces.

Connor, Michael. 2013. "Sustaining Undersea Dominance." *Proceedings* 139 (6): 1,324. http://www.usni.org/magazines/proceedings/2013-06/sustaining-undersea-dominance.

———. 2015. "Advancing Undersea Dominance." *Proceedings* 141(1): 1,343. http://www.usni.org/node/48368.

Dilshan, Silva, Moustafa Ghanem, and Yike Guo. 2012. "WikiSensing: An Online Collaborative Approach for Sensor Data Management." *Sensors* 12 (10). doi:10.3390/s121013295.

DOD CIO. 2010. "Department Of Defense Architecture Framework." DODAF v 2.02. August. http://dodcio.defense.gov/dodaf20.aspx.

Doswald-Beck, Louise (ed.) 1995. *San Remo Manual on International Law Applicable to Armed Conflicts at Sea*. Cambridge, MA: Cambridge University Press.

Edwards, Joshua, and Dennis Gallagher. 2014. "Mine and Undersea Warfare for the Future." *Proceedings* 140 (8): 1,338. http://www.usni.org/magazines/proceedings/2014-08/mine-and-undersea-warfare-future.

Emmersen, Tracy, Ng Kiang Chuan, David Chiam, Ong Zi Xuan, Perh Hong Yih Daniel, Koh Wee Yung, Wes Wessner, et al. 2011. "Advanced Undersea Warfare Systems." Capstone, Naval Postgraduate School. http://hdl.handle.net/10945/6959.

Everhart, Dave. 2012. "Advanced Undersea Weapon System." *10th International Mine Warfare Technology Symposium*. https://cle.nps.edu/access/content/group/3edf6e90-24e8-4c31-bffd-0ee5fb3581a6/public/presentations/Tues%20pm%20A/1330%20Everhart%20AUWS.pdf.

Floore, Timothy, and George Gilman. 2011. "Design and Capabilities of an Enhanced Naval Mine Warfare Simulation Framework." *2011 Winter Simulation Conference*, 2612–2618. Phoenix, AZ: IEEE. http://www.dtic.mil/dtic/tr/fulltext/u2/a558521.pdf.

Frank, David, Kevin Hogan, Shane Schonhoff, Nicole Becker, Timothy Byram, Richard Kim, Glenna Miller, Scott Myers, and Heather Whitehouse. 2014. "Application of Model-Based Systems Engineering (MBSE) to Compare Legacy and Future Forces in Mine Warfare (MIW) Missions." Capstone, Naval Postgraduate School. http://hdl.handle.net/10945/44659.

Greenert, Jonathan. 2011 "CNOs Sailing Directions." Washington, DC: U.S. Navy. http://www.navy.mil/cno/cno_sailing_direction_final-lowres.pdf.

Hart, Jane, and Kirk Martinez. 2006. "Environmental Sensor Networks: A Revolution in the Earth System Science?" *Earth-Science Reviews* 78: 177–191. http://eprints.soton.ac.uk/263093/1/esn.pdf.

Haskins, C. 2010. *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. Version 3.2. San Diego, CA: International Council of Systems Engineering.

Hayter, Anthony. 2012. *Probability and Statistics for Engineers and Scientists*. Boston, MA: Brooks/Cole.

Heath, Brian Raymond Hill and Frank Ciarallo. 2009. "A Survey of Agent-Based Modeling Practices (January 1998 to July 2008)." *Journal of Artificial Societies and Social Simulation.* 12 (4). http://jasss.soc.surrey.ac.uk/12/4/9.html.

Holmes, Eric, Barry Bakos, and Randy Hill. 2014. "Undersea Mine Warfare Capability." *NDIA*: *Undersea Warfare Division Newsletter*. Middletown, RI: Rite-Solutions. http://www.ndia.org/divisions/divisions/underseawarfare/documents/newsletter - fall 2014.pdf.

Hunt, Lee. 1998. "Mines Remain the Weapons that Wait." *Proceedings* 124 (3): 1,143. http://www.usni.org/magazines/proceedings/1998-05/mines-remain-weapons-wait.

ISO/IEC 14764-2006. International Standard for *Software Engineering – Software Life Cycle Processes – Maintenance*.

Jamshidi, Mo. 2009. *Systems of Systems Engineering: Principles and Applications*. Boca Raton, FL: CRC Press.

The Joint Staff. 2015. "Joint Capabilities Integration and Development System." CJCSI 3170.01I. Washington, DC: Joint Staff.

———. 2013. Joint Targeting. JP 3–60. Washington, DC.

———. 2015. *Manual for the Operation of the Joint Capabilities Integration and Development System* (JCIDS-M). 12 February 2015. Washington, DC.

———. 2015. Universal Joint Task List (UJTL). Updated thru September 2015. Washington, DC: Joint Staff. http://www.dtic.mil/doctrine/training/ujtl_tasks.pdf.

Long, David and Zane Scott. 2011. *A Primer for Model-Based Systems Engineering*. 2nd ed. Vitech.

LML Steering Committee. 2013. LML Specification 1.0. http://www.life cyclemodeling.org/spec/LML_Specification_1_0.pdf.

Lu, Han-Chung. 1992. "Using Expert Systems in Mine Warfare." Thesis, Naval Postgraduate School. http://www.dtic.mil/dtic/tr/fulltext/u2/a247758.pdf.

Madni, A. M. and Sievers, M. 2014. "Systems Integration: Key Perspectives, Experiences, and Challenges." *Systems Engineering* 17: 37–51. doi: 10.1002/sys.21249.

McFadden, Sharon, Jennifer Jeon, Annie Li, and Annalisa Minniti. 2008. "Evaluation of Symbol Sets for Naval Tactical Displays." Technical Report TR 2007–046. Toronto, CA: Defense R&D.

Meadows, Donella, and Diana Wright. 2008. *Thinking in Systems: A Primer*. White River Junction, VT: Chelsea Green Pub.

METRON. 2015. “Mine Warfare Capabilities Evaluation Tool.” *Operations Research and Cyber Analysis*. http://www.metsci.com/division/orca/mine-warfare-capabilities-evaluation-tool-mcet-copy.

Naval Surface Warfare Center. 2015. “Mine Warfare Systems.” Washington, DC: NAVSEA. http://www.navsea.navy.mil/nswc/panamacity/pages/mwsystems.aspx.

Niazi, Muaz A., and Amir Hussain. 2011. “A Novel Agent-Based Simulation Framework for Sensing in Complex Adaptive Environments.” *IEEE Sensors Journal* 11 (2): 404–412. doi:10.1109/JSEN.2010.2068044.

Object Management Group (OMG). 2015. Systems Modeling Language. Ver 1.4. Needham, MA: OMG. http://www.omg.org/spec/SysML/1.4/PDF.

Office of Naval Research. 2010. “Fact Sheet: Undersea Warfare Autonomy in ASW and MIW.” http://www.onr.navy.mil/~/media/files/fact-sheets/32/undersea-warfare-autonomy-submarine-mine.ashx.

Office of Naval Research, and M.W. Winter. 2015. *Naval S&T Strategy: Innovations for the Future Force*. http://www.onr.navy.mil/about-onr/~/media/files/about-onr/2015-naval-strategy-final-web.ashx.

Ponirakis, Lore-Anne. 2014. “Offensive Mine Warfare (MIW) Planning and Assessment Software Framework.” *Navy SBIR 2015.1 - Topic N151-071*. Office of Naval Research. December 12. http://www.navysbir.com/n15_1/n151-071.htm.

Pressman, Roger, and Bruce Maxim. 2015. *Software Engineering: A Practitioner’s Approach*. 8th ed. New York, NY: McGraw Hill.

Program Executive Office Littoral and Mine Warfare. 2009. *21st-Century U.S. Navy Mine Warfare: Ensuring Global Access and Commerce.* Washington, DC: U.S. Navy. http://www.navy.mil/n85/miw_primer-june2009.pdf.

Rice, Joseph. 2013. “Maritime In Situ Sensing Inter-Operable Networks.” Master’s thesis, Naval Postgraduate School. http://www.onr.navy.mil /reports/FY13/oarice.pdf.

Stellman, Andrew and Jennifer Greene. 2005. *Applied Software Project Management.* Sebastopol, CA: O’Reilly Media.

Stephens, D. G., and M. D. Fitzpatrick. 1999. “Legal Aspects of Contemporary Naval Mine Warfare.” *Loyola of Los Angeles Int’l & Comp. Law Review* 21 (4): 553. http://digitalcommons.lmu.edu/ilr/vol21/iss4/1.

Truver, Scott. 2011. "A Point of View: What 'Weapons That Wait?'" *SEAPOWER*. http://www.seapower-digital.com/seapower/201106#pg8.

United States Department of Defense. 2013. "Unmanned Systems Integrated Roadmap: FY2013-FY2038." Washington, DC: DOD.

United States Department of the Navy. 2010. *Naval Mine Warfare*. NWP 3-15 Volumes I and II. Washington, DC: U.S. Navy.

———. 2007. "Universal Naval Task List." OPNAVINST 3500.38B. Washington, DC: U.S. Navy. http://www.uscg.mil/hq/cg5/cg513/docs/UNTL_ver_3.0_Jan_07.pdf.

Washburn, Alan. 2007. "Minefield Models." Master's thesis, Naval Postgraduate School. http://faculty.nps.edu/awashburn/Files/Notes/MinWar.pdf.

Wilensky, Uri. 2015. "The NetLogo User Manual." Evanston, IL: Northwestern University. http://ccl.northwestern.edu/netlogo/docs/.

Wu, Qishi, Mengxia Zhu, Nageswara Rao, Sitharama Iyengar, Richard Brooks, and Min Meng. 2009. "An Integrated Intelligent Decision Support System Based on Sensor and Computer Networks." Chapter 11 in *Systems of Systems Engineering: Principles and Applications,* edited by M. Jamshidi, 281–317. Boca Raton, FL: CRC Press.

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California